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Mechanical Tests for Engineering Materials.

(Revised Reprint).

By A. M. ROBERTS, B.Sc., Wh.-Ex., A.M.I.M.E.

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CONTENTS

MECHANICAL TESTS FOR ENGINEERING MATERIALS.

A. M. Roberts.

During the past century an elaborate and comprehensive technique for the testing of engineering materials has grown up from very simple beginnings. Development at first proceeded slowly, but was later accelerated as it came to be appreciated that engineering requirements had outstripped the available materials.

With progress and acquisition of a better knowledge of materials, gained generally through failures, the procedure of testing has now become increasingly complex and searching and, although it has for many purposes been in a more or less established form for a number of years past, further developments are now proceeding to meet the requirements of new materials and new operating conditions.

The improvements in engineering, particularly for power installations, have introduced during recent times novel and more severe conditions under which structural materials must operate with safety. The need for new or better materials has led in these special cases to the development of more stringent or to entirely new forms of testing.

Acceptance tests are now so generally demanded and employed for materials of all classes of engineering structures and machines that one can accept without question the proved value and importance of the usual forms of test procedure about which many excellent treatises have been written, more especially for the testing engineer.

The excuse for introducing yet another publication on this subject is to be found in the need for a brief treatment giving concisely the methods and purposes of the more usual forms of test, which it is hoped will be sufficiently comprehensive to meet most of the needs of the designer or draughtsman without introducing details and arguments, which are only of real value to the person actually engaged in testing.

The pamphlet is, therefore, written specifically for the engineer and draughtsman who, unfamiliar with testing methods, meets the problem of deciding what tests it is necessary to apply to the machine or structural part which he has designed and for which he wishes to ensure a satisfactory performance under the service conditions with which he is acquainted.

It seems safe to assume that the majority of engineers and draughtsmen rarely get the opportunity of gaining testing experience at first hand and for this reason, without digressing into descriptions of obscure forms of tests, the more frequently used tests and testing equipment are described in some detail, and are arranged as far as possible in the order of their popularity. It should, of course, be borne in mind that some of the less frequently used forms of test may be of primary importance for particular applications. Certain tests falling into this category are referred to briefly.

In many instances the choice of material for a particular part is pre-defined by specifications or other considerations and in these cases it is only necessary to design within the known properties of the particular material.

For other cases greater freedom may exist and the designer may be permitted to select the material in addition to deciding on the form and size of a machine part which will safely withstand the applied loads under the special conditions which occur.

The usual forms of tensile, bend, hardness and impact tests are described in some detail and the relation of the structural part under consideration and its service condition to the appropriate test procedure is discussed. A few suggestions are also made as to the method of approach in designing a part for service under static, dynamic or other special conditions.

THE TENSILE TEST.

The testing of materials by measurement of the tensile load required to rupture standard-sized specimens is most probably the oldest form of test used for the selection of materials.

This type of test still retains its popularity and is more widely employed than any other single test.

In its modern form the tensile test is frequently used to obtain measurements of the ductility of a material in addition to the tensile strength ; also other properties, such as elastic limit, yield point, modulus of elasticity, etc., which later are dealt with in detail.

1. TENSILE TESTING MACHINES.

The essentials of a testing machine consist of (1) means for gripping the sample of material, which are similar in most types of machine, together with mechanism capable of (2) applying and (3) measuring the load transmitted to the specimen *via* the specimen grips.

Practically all types of testing machine are covered by combinations of these three essential parts, viz. :—

(1) **Specimen Grips.**

(*a*) Split, tapered jaws with serrated surfaces, which automatically increase the grip on the specimen with increasing load;

or (*b*) Threaded shackles to take the screwed ends of the specimens;

or (*c*) Split-chuck with "keep" ring for use with "dumb-bell" type specimens.

(2) **Straining Mechanism** which may consist of—

(*a*) Screw mechanism, motor driven through reducing gears;

or (*b*) Hydraulic ram with its associated pump and accumulator.

(3) **Load Measuring Device,** either—

(*a*) Single or multi-lever arrangement with jockey type balancing weight;

or (*b*) Pressure gauge coupled to hydraulic loading ram, calibrated to read the load or stress carried by the specimen.

It is not possible within the scope of the present article to discuss all the various arrangements and combinations of the above parts which may occur in testing machines, and it is proposed to confine the descriptions to a typical motor-driven lever machine and to a hydraulic machine with gauge recording, brief reference being made to other types in common use.

A. Single Lever Testing Machine.

The real development of testing machines commenced in the early part of the 18th century and the first few years saw the introduction, in a simple form, of practically all types of machine in use at the present day.

Because of the necessity for measuring heavy loads, the value of a multiplying lever and jockey weight was soon apparent and, although this mechanism was also capable of applying load, its use for this purpose was only possible for materials such as cast-iron, where the extension of the specimen was negligible.

This limitation made it necessary to devise means for absorbing the extension of a ductile specimen at one end, in order that the load measuring lever linked to the other end could be maintained floating in an approximately stationary position.

In this manner the single lever testing machine was evolved, a typical arrangement of which is shown by the diagram, Fig. 1, in which the upper end of the specimen A is attached by grips to the saddle C, which in turn is carried on knife edge supports from the short end of the lever D.

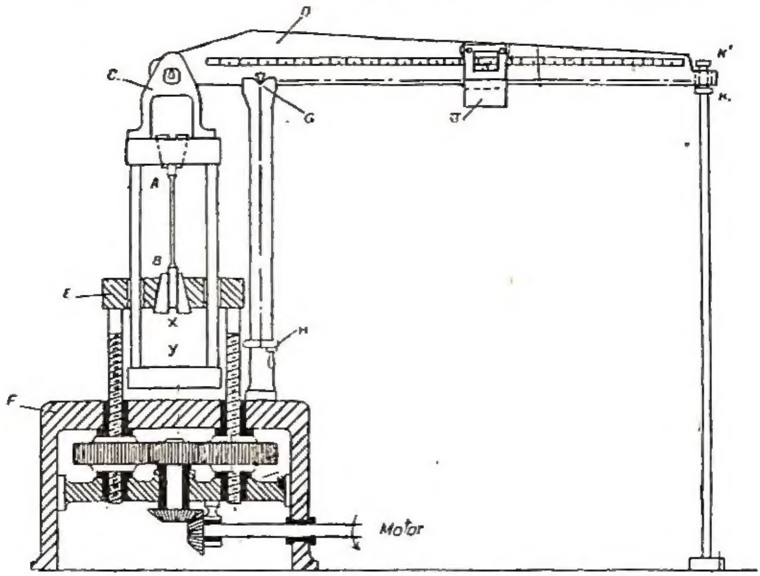


Fig. 1—Single Lever Testing Machine.

At the lower end B, the specimen is attached by grips to the cross-head E, which is motor-driven through the screw and gear wheel mechanism, enclosed by the box type of machine table F.

The load measuring lever D is supported on a knife edge fulcrum G, formed in the upper end of a pillar secured to the table F.

A jockey weight J, controlled by gearing from the handle H, together with a scale of load, is carried on the long arm of the lever, which is limited in its angular movement by the stops K and K_1 fixed to an independent support at the free end of the lever.

With the arrangement as shown, tensile tests are made with the specimen secured in the space AB, whilst compression tests can be carried out by placing the specimen in the gap X, Y. For both types of test the straining of the specimen and the load measurements are conducted in a similar manner.

During a test, either in tension or compression, after securing the specimen in position, the motor-driven straining machanism is set into operation and as the load on the specimen rises this is continuously measured by rotating the wheel H to move the jockey weight further out along the lever, taking care to maintain the free end of the lever floating between the stops K and K_1.

A good example of this type of machine is shown by the 20-ton Avery machine in Fig. 2, which also incorporates means for testing in torsion.

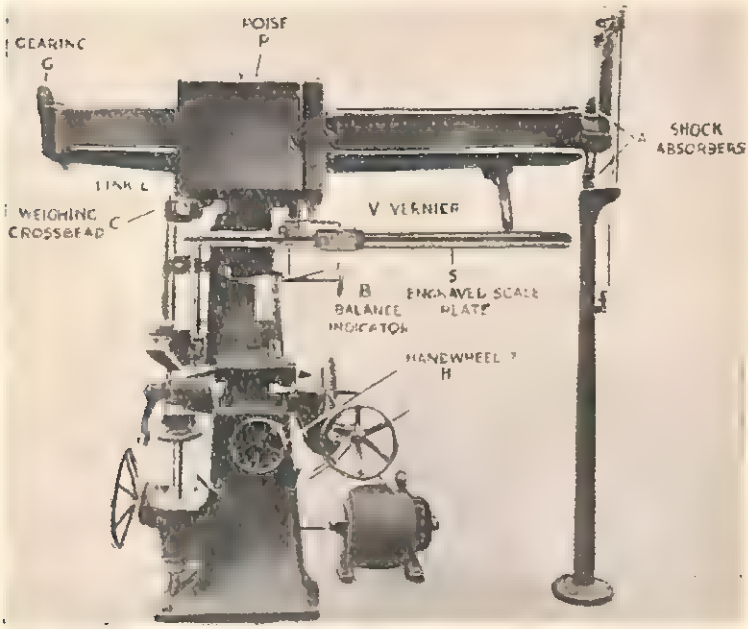


Fig. 2.

B. Hydraulic Testing Machine.

The essentials of a simple type of hydraulic testing machine with pressure-gauge load recording are shown by the diagram, Fig. 3.

In this arrangement the tensile specimen AB is secured at its lower end A by grips to the cross-head C, which in turn is supported from the base plate by the screwed pillars D and D^1.

Forked ends are formed on the cross-head C, in the prongs of which two large nuts, E and E^1, are housed, these engaging with the screwed pillars D and D^1.

Teeth are provided on the outer face of the nuts, which are rotated by means of gearing driven by the hand-wheel F, permitting the cross head C to be raised or lowered at will.

At the upper end B, the specimen is attached by grips to a second cross-head G, supported by rods from the hydraulic-loading ram H.

The ram is housed in a cylinder supported from the upper end of the screw pillars D and D^1 and is fed by the pipe J connected with the hydraulic pressure supply.

At a convenient point in the pipe J, adjacent to the cylinder, a branch is led off to the pressure gauge K, calibrated for total load on the ram, which, neglecting a small frictional loss, is equal to the load carried by the specimen.

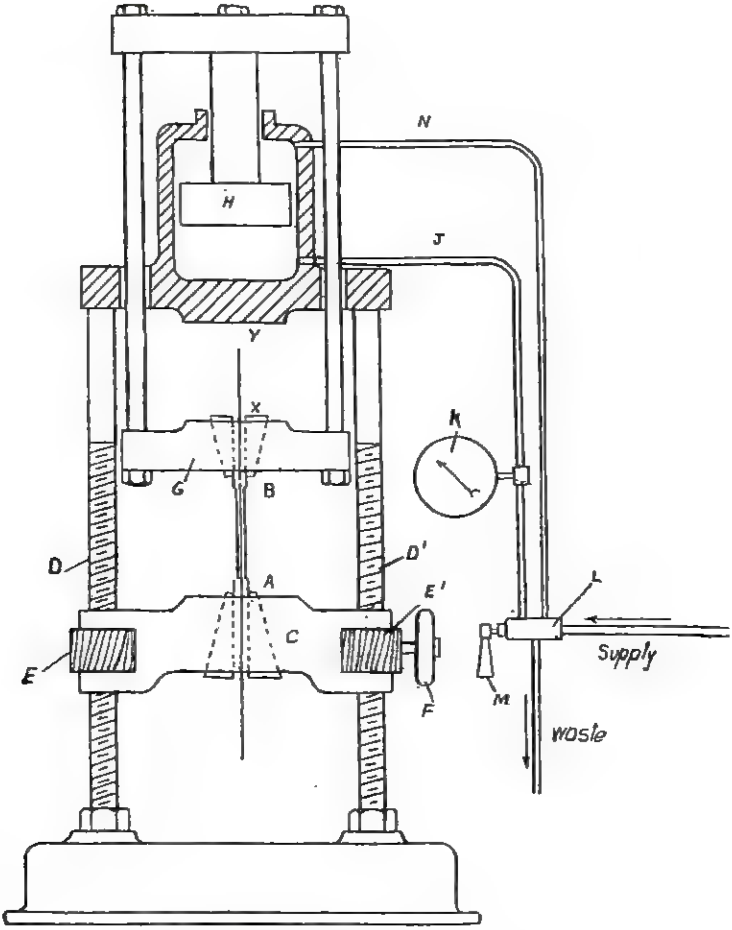


Fig. 3—Simple Hydraulic Type Testing Machine.

Immediately on the supply side of the branch pipe a control valve L is interposed in the piping, this being operated by a handle M, generally situated, as shown by the sketch, in a convenient position near to the gauge K.

The return stroke of the ram is obtained by feeding pressure to the opposite end of the cylinder through the pipe N, this reverse action being controlled from the valve L, which automatically connects the opposite side of the ram with the waste pipe.

For the purpose of compression testing the space XY between the base of the cylinder and the cross-head G is conveniently employed, although on some types of machine a further cross-head linked to G is supported below the cross-head C, the space between the two then being employed for compression testing.

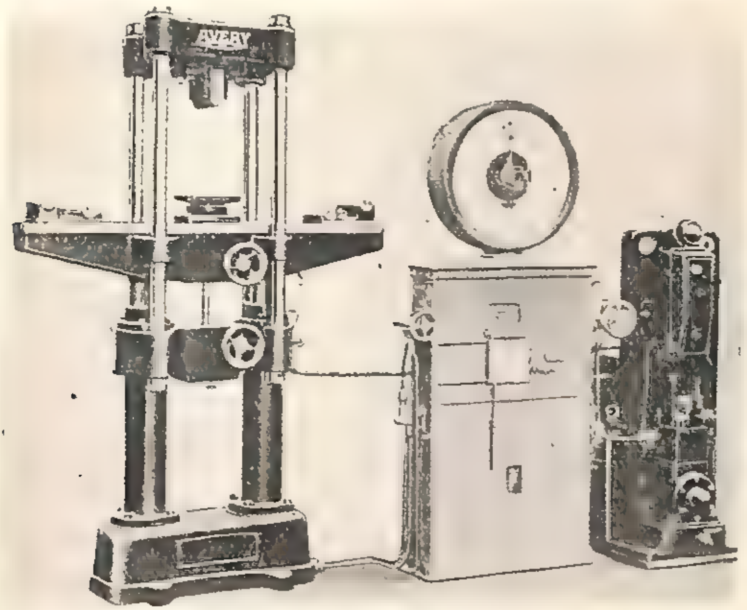


Fig. 4.

Two examples of well-designed hydraulic testing machines are shown by the 50-ton Avery machine, Fig. 4, and the 50-ton Amsler machine, Fig. 5.

The Avery machine employs two cylinders and rams for loading, these being connected through a sensitive control valve to a motor-driven reciprocating pump, load on the specimen being recorded by a pointer moving over a large dial provided with high and low range scales.

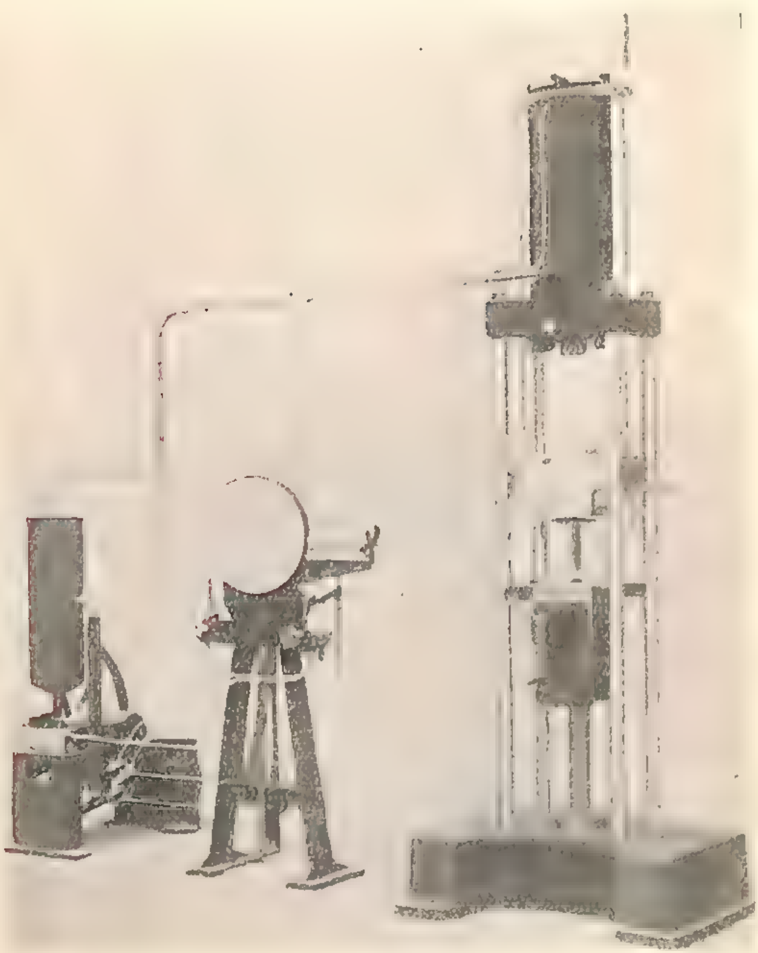


Fig. 5.

In the Amsler arrangement a single overhead cylinder and ram is employed, this being fed from a reciprocating pump connected through a sensitive control valve.

Load measurements with this machine are obtained by the use of a special pendulum dynamometer, fitted with a pointer and dial recording mechanism.

Both machines are fitted with apparatus for taking stress-strain records of the test.

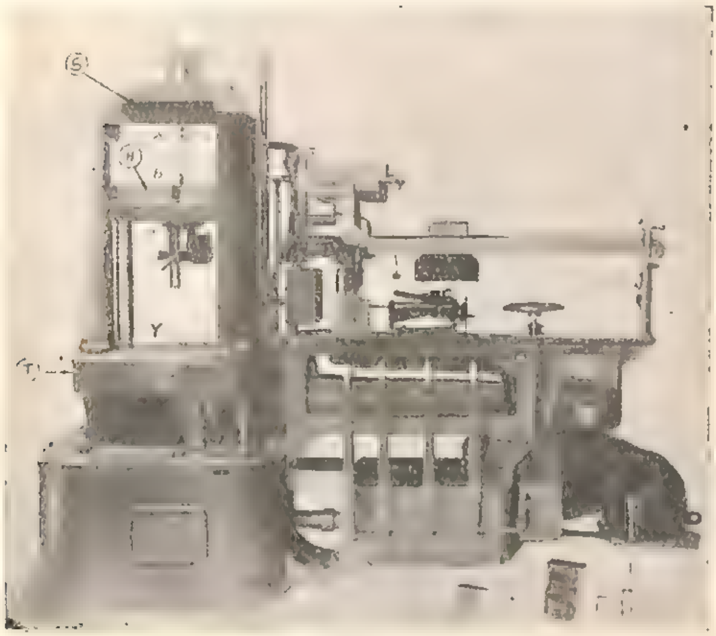


Fig. 6.

C. Other Types of Tensile Testing Machine.

The two types of testing machine which have been described (1) all mechanical straining and load measuring devices and (2) hydraulic straining and load measurement, form the basis on which many variations in design have been built up.

Although hydraulic machines have advantages for rapid testing, the mechanically-operated machines are probably the most generally popular types and of these, whilst the single lever machine has the important feature of simplicity, this type is being superseded by multi-lever machines, which permit of more accessible designs and a greater economy in floor space.

The Olsen multi-lever machine, Fig. 6, is a good example of this type of apparatus, in which the single lever is replaced by three

levers, the last of which forms the graduated arm carrying the jockey weight.

In this machine, the table T and its associated bridge S are supported on what is virtually the short arm of the lever, any load applied either to T or S being balanced and measured by moving the jockey weight to a suitable position.

The straining head H is moved vertically up or down by means of a motor driving through gearing and a screw-and-nut mechanism.

Movement of H is quite independent of the table T and connection between these two parts is only established through the specimen under test.

Tensile specimens are accommodated in the gap AB and are secured at their opposite ends by grips to S and H respectively.

Compression tests are carried out by placing the specimens in the space XY.

This arrangement ensures that no matter whether the test specimen is under tension or compression the resulting load on the table T is vertically downwards and can be measured by balancing with the jockey weight.

A number of other forms and variations of testing machines are in existence, but these, with one or two exceptions, are based on the main types already described.

Certain specially-designed tensile or compression machines, such as are extensively used for the testing of chains and large springs, are also based on the same general principles and can be readily understood by reference to the descriptions previously given.

2. THE TENSILE SPECIMEN.

For practically all purposes tensile specimens are arranged with a parallel central portion of uniform section, which is provided with enlargements at both ends of suitable shape and length for securing in the grips of the testing machine.

A few exceptions to this general rule do occur, notable examples being small tubes, strip materials, rods and wires, all of which are frequently tested in tension without any modification to their sections.

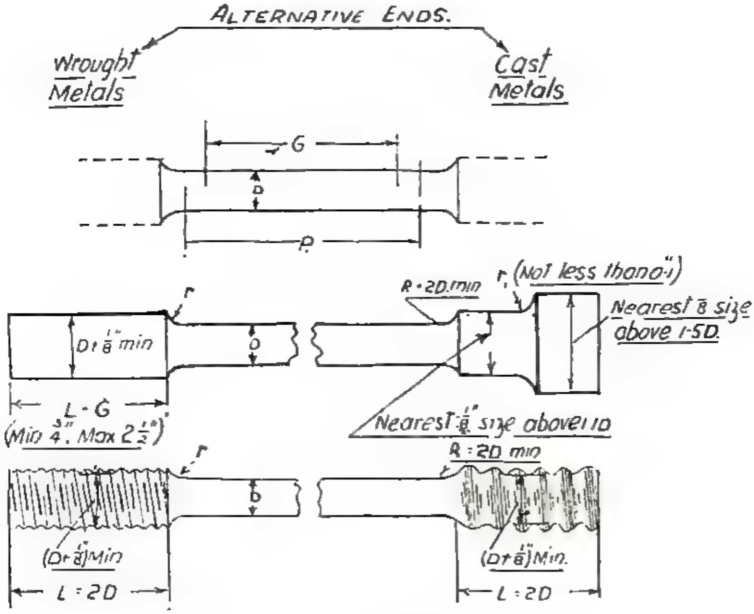
Apart from such cases, the precise forms of test specimens which are used for the various materials are entirely governed by the character of the material and the tensile properties which it is desired to measure.

The various forms of test specimens are now largely stabilised and are fully defined by the B.S.I. and other specifications.

Some of the more important of these forms of specimen, together with notes on the materials for which they are intended, are described below.

TABLE No. 1.

TENSILE SPECIMENS—(1) Turned.



All Dimensions in Inches.

Dis. D.	Sectional Area A.	Gauge Length G.	Parallel Length P.	Radius *r*.
0·226	0·040	0·80	1·0	0·25
0·357	0·10	1·25	1·5	0·3125
0·564	0·25	2·00	2·25	0·50
0·798	0·50	3·00	3·375	0·75

Note.—For Cast Metal, R=2 D. min. B.S.I. requirements, R=4·4 D. min.

A. Round, Machined Specimens.

The more common forms and sizes of turned specimens are given by Table No. 1, in which it will be found that the diameter D and gauge length G are approximately connected by the relation :—

$$\text{Gauge length G} = 4\sqrt{\text{Sectl. Area A}} = 3{\cdot}54 \text{ D}$$

Such small discrepancies as exist between this relation and the dimensions given in the table are accounted for by the important advantage in having areas and gauge lengths which lend themselves to rapid calculation rather than a rigid adherence to the above rule.

Specimens having the proportions given in the table are employed for a very wide range of materials, including :—

(1) Steel forgings.
(2) Steel castings.
(3) Iron castings.
(4) Non-ferrous metals and alloys.
(5) The large sizes of plate and bar materials.

The form of the ends of the specimens and the radii joining the parallel length with the ends depend largely on the ductility of the material being tested.

In the case of ductile materials, such as most steels and wrought non-ferrous metals, the ends are either left plain for use with serrated vee-grips, Fig. 7B, or are screwed with a suitable Whitworth thread for adaption to screwed shackles, shown by Fig. 7D.

Materials of negligible or low ductility, such as cast-iron and certain cast non-ferrous metals, should be preferably tested in self-aligning shackles, Fig. 8, the specimen being provided with dumb-bell ends, as shown by the sketch in Table 1.

Another form for the ends of the specimen which is occasionally employed for certain cast non-ferrous metals is also shown in Table 1, the ends in this case being finished with a rope thread fitting into a similarly-threaded shackle.

The object of the rope thread is to avoid failure across the threads due to high stress concentrations, such as occur with vee'd threads.

With ductile materials it has been found satisfactory to make the transition radii equal to the diameter of the parallel portion, but in the case of cast-iron and other materials of low ductility it is necessary to increase this radius to at least twice this value in order to avoid fracture through stress concentration at the transition point.

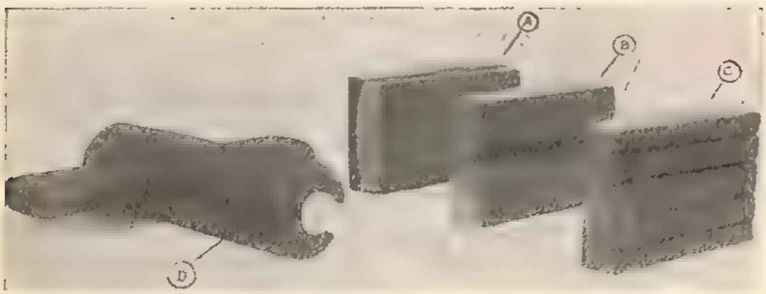


Fig. 7.

B. Flat, Machined Specimens.

Table 2 gives the more frequently used sizes of specimens which are employed in the testing of plate materials, flats and also tubes above $1\frac{1}{4}''$ diameter. Smaller tubes are tested in the unmachined condition.

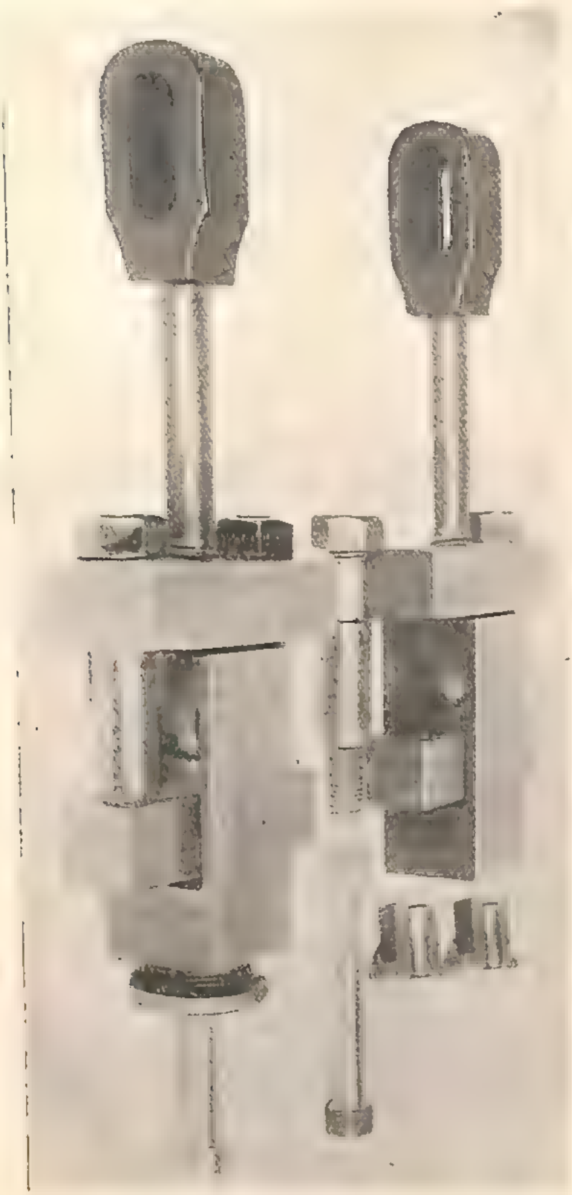


Fig. 8.

As will be evident from the sketches, the test specimen is cut from the plate or tube in the form of a parallel strip, which is afterwards reduced in width over the centre test-portion in order to ensure that fracture will occur within this region. It should be noted that only the ends of tube specimens are permitted to be flattened, the gauge length being left in its original form.

Flats are generally merely reduced in width over the parallel test length, otherwise being left in their original condition.

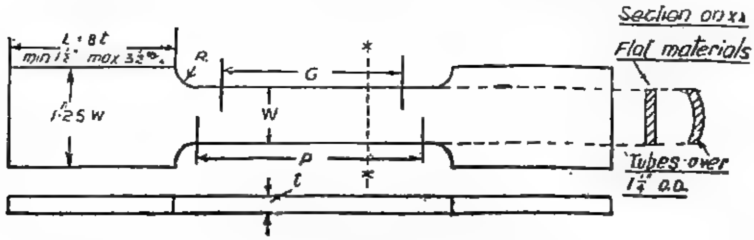
Suitable tapered grips for use in testing flat specimens are shown by Fig. 7, A and C, the former being of the self-adjusting type, which ensures axial loading when the ends are of irregular thickness.

C. Unmachined Specimens.

In many cases of bars and rods, both round and polygonal, it is convenient and economical to carry out tests on sample lengths cut from the consignment without further machining.

TABLE No. 2.

TENSILE SPECIMENS—(2) Machined from Flats and Tubes.

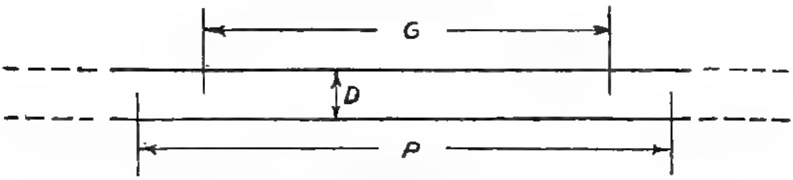


All Dimensions in Inches.

Thickness t.	Width W.	Gauge Length G.	Parallel Length P.	Radius R.
Under 0·125	0·5	2·0	2·5	1·0
0·125 to 0·25	1·0	4·0	4·5	1·0
0·25 to 0·875	2·0 max.	8·0	9·0	1·0
Over 0·875	1·5 max.	8·0	9·0	1·0

Note.—The parallel length of specimens cut from tubes must not be flattened.

(3) Unmachined Bars.



D = Diameter or width across flats.
G = Gauge length.
P = Length between grips.

Dimension D.	Gauge Length G.	Length Between Grips
1" and less,	8 D	9 D
Above 1"	8 D	4·5 D

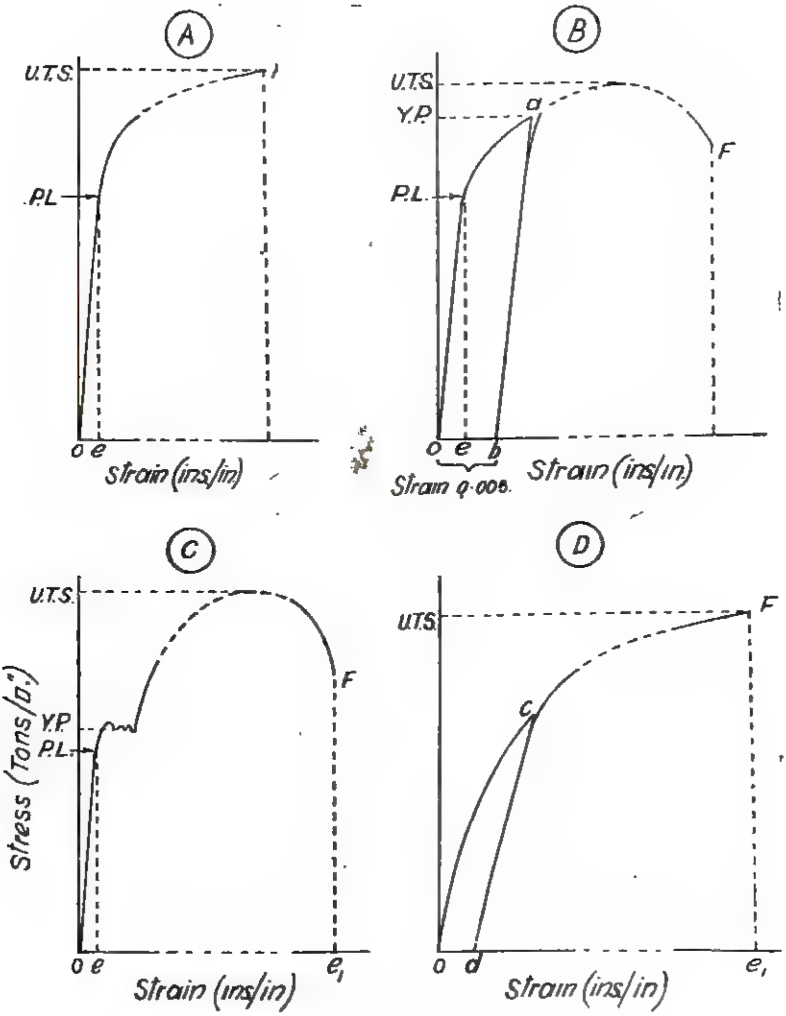

A
U.T.S.
P.L
o e
Strain (ins/in)
B
U.T.S.
Y.P.
a
F
P.L.
o e b
Strain 0·005.
Strain (ins/in)
C
U.T.S.
F
Y.P.
P.L.
Stress (Tons/□")
o e
e1
Strain (ins/in)
D
U.T.S.
F
c
o d
e1
Strain (ins/in)

Fig. 9.

For such tests the proportions of the test specimens are set out in the lower section of Table 2 and suitable grips are shown by Figs. A, B and C, choice between these depending on the sectional form of the specimen.

3. TENSION TESTS.

When a metal tensile specimen is subjected to a steadily increasing load, it will extend in most cases proportionately to the load until a point is reached varying with different materials, after which the extension increases at a progressively greater rate than the loading, and failure by rupture finally occurs. Such measurements of the extensions of a specimen may be made by means of an extensometer or by an autographic stress-strain recorder, such as is fitted to machines, Figs. 4, 5 and 6.

If the load per square inch (stress) and the corresponding extension per inch (strain) are noted at progressively increasing loads throughout the test and these are afterwards plotted, it will generally be found that the resulting curve corresponds approximately with one or other of the four forms, A, B, C or D, shown by the diagram, Fig. 9, which represents the types of stress-strain curves generally found with the following materials :—

Fig. 9.	Materials Represented.	Remarks.
A.	Certain non-ferrous metals and hard steels.	Line up to PL straight, defines range where stress is proportional to strain. No defined Yield Point. Specimen breaks at maximum stress.
B.	Alloy Steels and Some Non-Ferrous Metals.	Line up to PL straight, defines range where stress is proportional to strain. No defined Yield Point. Specimen breaks after maximum stress has been passed.
C.	Mild and medium carbon steels.	Line up to PL straight, defines range where stress is proportional to strain. No defined Yield Point. Specimem breaks after maximum stress has been passed.
D.	Certain non-ferrous metals and cast-iron.	Line curved from commencement has no range where stress is proportional to strain. No defined Yield Point. Specimen breaks at maximum stress.

In these diagrams the slope of the line from zero up to the point marked PL has been exaggerated out of proportion to the remainder

of the diagram, in order to distinguish it clearly from the vertical ordinate ; it should also be noted that the strain scales for the curves may be very different for the different materials represented.

In all previous and succeeding references to tensile testing, including Fig. 9, it should be understood that, in line with normal practice, the ultimate stress, the yield point stress, the proof stress, and the proportional limit stress are calculated respectively by dividing the ultimate load, the yield load, etc., by the original unstressed sectional area of the test specimen.

Occasionally for academic reasons, tests are made in which the above results are deduced from the sectional area measured after or during the application of the load. Such quantities are of little general interest and are outside the scope of the present pamphlet.

A. Ultimate Tensile Stress.

In the case of all four diagrams, the maximum stress attained during the test is marked on the stress ordinate as U.T.S., indicating the ultimate tensile stress which the material is capable of sustaining.

B. Proportional Limit.

Referring to diagrams A, B and C, it will be observed that starting at zero the first part of the record is straight, but inclined to the vertical, although following this phase, the line becomes increasingly curved until fracture occurs at the point F.

The stress corresponding with the point PL where the line ceases to be straight is known as the proportional limit stress, whilst the corresponding strain e is known as the proportional limit strain. To obtain reliable values for the proportional limit, it is necessary to use an extensometer.

C. Yield Point.

It will be observed on the diagram C that the shape of the line immediately above the PL point indicates an erratic but comparatively sudden extension of the specimen with very little change of load.

This behaviour is typical of mild carbon steels and occurs with practically no other metal ; the stress at this point is known as the yield point stress.

It was this phenomenon in carbon steels which led to the general adoption of yield point measurements in the case of practically all tests on metals, although in the majority of cases no sudden yielding takes place in the same way as with carbon steels.

In the absence of such yielding, it has become the practice to define the yield point as the stress at which a permanent strain of 0·005 inch per inch occurs. This is shown diagrammatically by

diagram B, where the line *ab* records the elastic recovery of the specimen as the load is removed down to zero, where the permanent strain $ob = 0{\cdot}005$.

Yield point measurements may be determined by means of an extensometer or autographic recorder, although in practice, as such methods, although accurate, are somewhat lengthy, it is more usual to note the point at which the rate of increase of load decreases suddenly whilst the machine is maintaining a constant rate of straining.

This condition, although it may appear rather involved, is very readily noted in the behaviour of the testing machine.

With the lever type of testing machine it will be found that in the early stages of the test the jockey weight has to be run out rapidly, but that shortly after the proportional limit is exceeded and yielding sets in there is a comparatively sudden slowing up in the rate at which the jockey has to be moved to maintain balance ; the load at this point is taken as the yield point.

In the case of hydraulic machines the yield point is readily noted by the hesitation or slowing up in the movement of the load-indicating finger as it passes round the dial.

Another common method for determining the yield point is to define the gauge length of the specimen with fine centre punch marks in which sharp-pointed dividers are held during the progress of the test. The yield point load is noted by the movement of one of the divider points out of its location in the punch mark.

It will be evident from the character of the stress-strain curves on Fig. 9 that with any of the above methods of yield point determination the measurement will be most clearly defined in the case of the mild and medium carbon steels.

D. Proof Stress.

The use of the property known as the "Proof Stress," to specify or define the mechanical performance of a metal, has now become common usage for aircraft materials.

"Proof Stress" is defined as "That stress at which the stress × strain curve departs by 0·1% of the gauge length from the straight line of proportionality."

It is usually determined from an extensometer "stress × strain" diagram and its value can be obtained in exactly the same way as the yield point is determined from the diagram B, except that in the case of the proof stress the strain *ob* is commonly taken as 0·001, although other values 0·002, etc., are sometimes used.

E. Young's Modulus.

Young's modulus, or the modulus of elasticity, is the property which defines the resistance to stretch of the material and is given by the relation

$$\text{Young's modulus } E = \frac{\text{stress}}{\text{strain}} = \frac{PL}{\varepsilon} = \text{slope of line O to PL on Fig. 9.}$$

It is the stress which would double the length of a bar on the assumption that the line from zero up to PL were continued at the same slope.

Because of the necessity of accurate measurements of the strain at and below the proportional limit, it is only possible to determine Young's modulus for tensile specimen by means of an extensometer.

In the case of materials having stress-strain characteristics, as shown by the diagram D, Fig. 9, which curve practically from the beginning, it is usual to determine Young's modulus from the slope of the line taken when the load is removed as indicated by *cd*.

F. Elongation and Reduction of Area.

A valuable and simple measure of the ductility (*i.e.*, capacity for deformation) of a material can be obtained from the ordinary tensile test.

This is done by measuring after fracture the elongation which has occurred over a specified length of the specimen known as the gauge length and also by the change in section at the position where the fracture occurs.

The gauge lengths and diameters normally employed are given in detail by Tables 1 and 2.

It is usual to record these measurements as the percentage elongation and the percentage reduction of area. Thus, if G and G_1 are the original and final lengths and D and D_1 the original and final diameters, then—

$$\text{Percentage elongation} = \frac{G_1 - G}{G} \times 100$$

and

$$\text{Percentage reduction of area} = \frac{D^2 - D_1^2}{D^2} \times 100$$

There appears to be no universal relation between the percentage elongation and the percentage reduction of area for different steels, and it is important to take both measurements in order to assess the ductility of any particular material.

Certain types of steel are found to give great reduction of the section at fracture with only moderate elongation, whilst other types of steel exhibit the reverse behaviour.

Both types have adequate ductility for all practical purposes, although, if judged from either measurement alone, one or other steel may appear to be of doubtful quality.

4. EXTENSOMETERS.

For purposes of design, in addition to obtaining measurements of the ultimate strength of metal samples, it is also frequently important to determine the relation between the stress and the corresponding tensile or compressive strains of the specimen under loads well below the yield point of the material.

An instrument for measuring these small strains in a test specimen is known as an extensometer, of which types are now in common use.

The basic principle of all extensometers is similar. Attachments are made to two positions on the test specimen separated by a known length, the relative movement of these attachments during loading of the specimen then being multiplied by a suitable means to give the required sensitivity of measurement.

The most frequently used methods for amplifying the movement of the specimen attachments, together with the names of typical extensometers in the particular classes, are given below.

Method of Amplification.	*Extensometer.*	
Fig. 10—Micrometer.	Cambridge	(Cambridge Inst. Co., Ltd.)
Fig. 11—Microscope.	Ewing	(,, ,, ,,)
Fig. 12—Optical Lever.	Martens	(Amsler)

To be of real value an extensometer should be capable of measuring strains accurately to 0·0001″ per inch of specimen and most types of instruments on the market are capable of this sensitivity at least.

In addition to the types of instrument referred to above, all of which necessitate a succession of readings being taken which are afterwards plotted, there is a wide range of autographic stress-strain recorders, which automatically record the stress-strain relation as the test proceeds.

This type of apparatus has generally much less sensitivity than the true extensometer and cannot be employed for delicate measurements such as the proportional limit and Young's modulus.

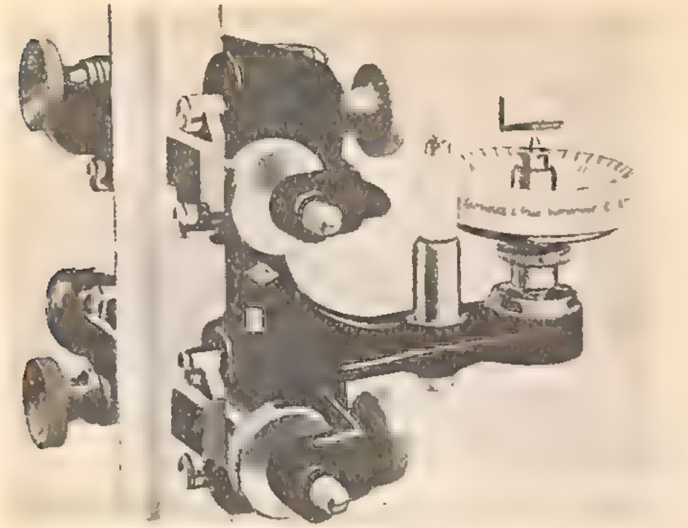
The majority of autographic recorders are entirely mechanical, and being generally supplied by the makers of testing machines are only suitable for use with the particular machine.

Another type of autographic recorder, designed by Professor Dalby, which is adaptable to most types of testing machine, employs an optical arrangement and gives a photographic record of the stress-strain relation. It is said to be very simple and rapid in operation.

THE BEND TEST.

5. BENDING TESTS.

The bending of a sample of cast or forged steel in order to prove its ductility is probably one of the oldest forms of material test



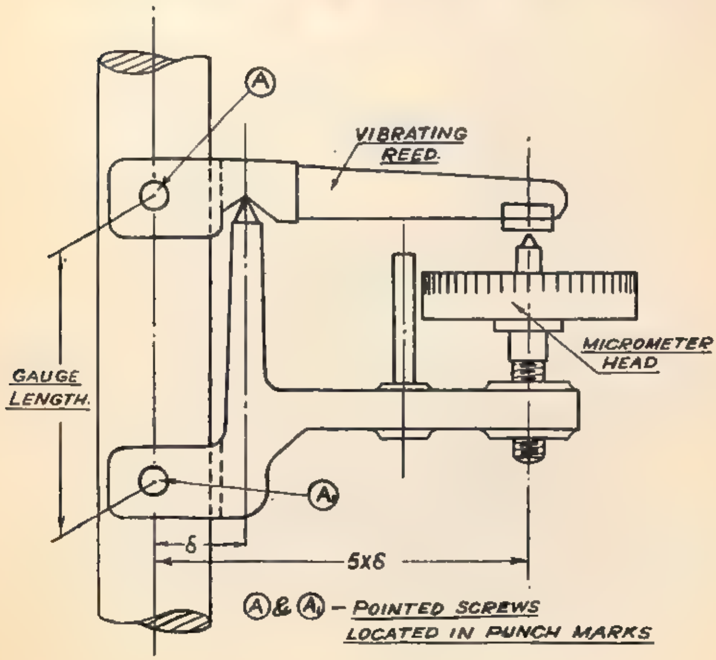

VIBRATING REED.
MICROMETER HEAD
GAUGE LENGTH.
δ
5xδ
Ⓐ & Ⓐ₁ – POINTED SCREWS LOCATED IN PUNCH MARKS

Fig. 10.

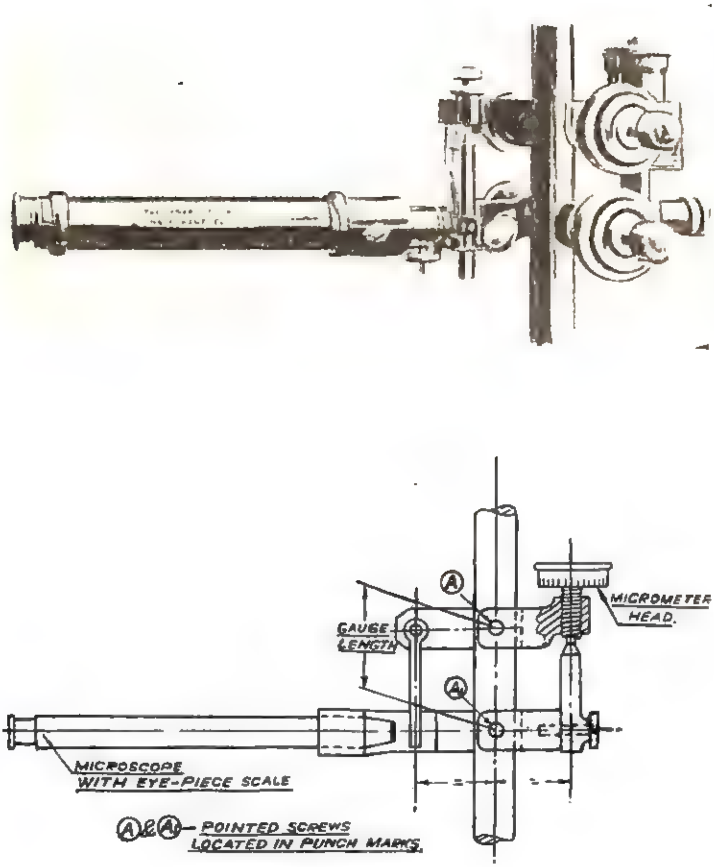

GAUGE LENGTH
MICROMETER HEAD.
MICROSCOPE WITH EYE-PIECE SCALE
A & A₁ – POINTED SCREWS LOCATED IN PUNCH MARKS.

Fig. 11.

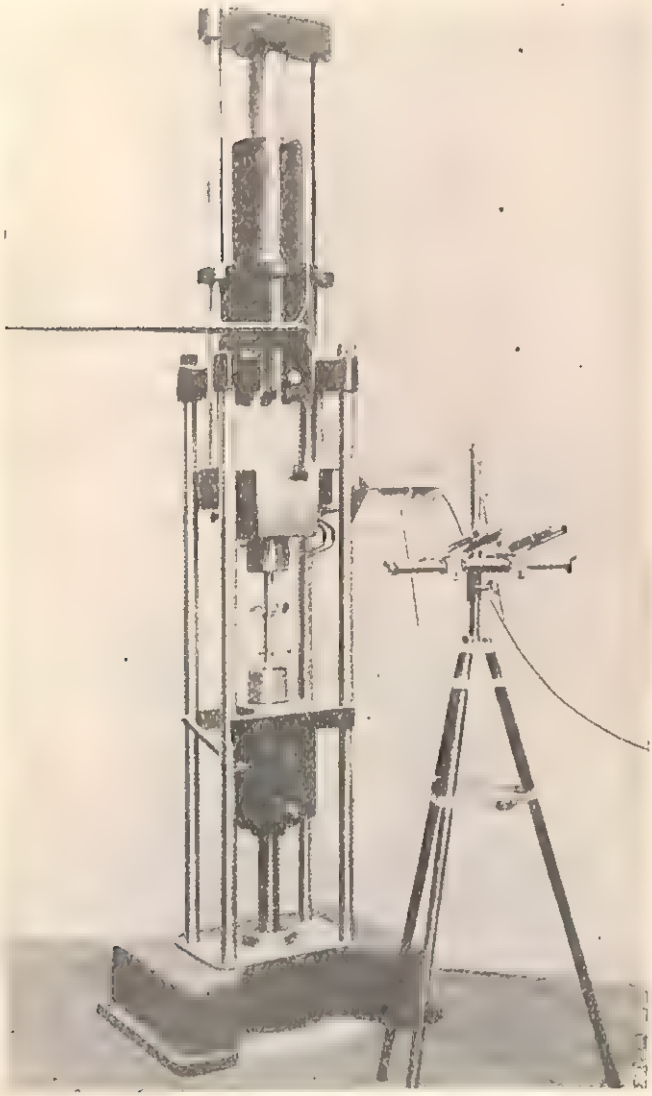


Fig. 12.

E

and, although it is peculiarly liable to misuse, this test can, under properly controlled conditions, supply valuable information by very simple means.

It is of primary importance that the test samples should be cut from the casting or forging after the final heat treatment and the location of the test material should be selected to be representative of the bulk of the material.

Specimens are generally machined in the form of rectangular section parallel bars, with the sharp corners afterwards carefully rounded by smooth filing, in order to reduce the chance of minute machining or material defects leading to a premature failure.

During test, the ends of the test bar rest on two rollers or fixed rounded supports, the bending then being carried out by means of a radiused former located at the centre of the span. This action is continued until the legs become parallel or some predetermined angle is obtained.

Bending equipment for use with any normal type of tension-compression testing machine is shown by the photograph, Fig. 13, which also includes a range of formers of different radii to suit the various test specifications.

Other types of bending equipment are in existence, but these are generally more complicated than the arrangement illustrated, without having any important advantage.

Fig. 13.

Where bend tests are required by an inspecting authority, the test conditions, details of the size of specimen, the radius of the former and the angle through which bending shall take place are laid down in the specifications for the material.

Some of the more common specifications are referred to later under the appropriate sections, but for convenience the usual sizes of bend specimens are tabulated below :—

Material.	Dimensions of Bend Specimen—Inches.			
	Length.	Width.	Thickness.	Corner Rad.
Mild Steel Forgings,	7 - 8	1	1	$\frac{1}{16}$
Mild Steel Forgings,	7 - 8	1	$\frac{3}{4}$	$\frac{1}{16}$
Carbon Steel Castings,	7 - 8	1	$\frac{3}{4}$	$\frac{1}{16}$
High Tensile Steel Forgings,	6	$\frac{3}{4}$	$\frac{3}{8}$	$\frac{1}{16}$
Alloy Steel Castings,	6	$\frac{3}{4}$	$\frac{3}{8}$	$\frac{1}{16}$

TESTS FOR HARDNESS.

The testing of metals for hardness has of recent years developed into a very important section of most works testing, and particularly so in the case of works concerned with the production of machine parts in large quantities.

One great advantage of this method of testing is the facility by which tests may be easily and rapidly carried out on machine parts at any stage in their production, in the majority of cases without involving waste of material for test purposes.

It should be noted that in most circumstances the hardness test is to be regarded as a method of checking the uniformity of treatment of a batch of similar parts and does not necessarily remove the need for tensile, bend or other tests on representative samples of the batch. Most hardness measurements can, however, be correlated to the tensile strength of the material and a conversion chart for steels is given by Table No. 3, which includes all the principal hardness tests used commercially.

The most frequent use of the hardness test is probably in checking the uniformity and accuracy of heat treatment operations, although operations involving the mechanical working of metals may also be checked for uniformity throughout a batch which has been subjected to uniform treatment.

A very wide range of hardness testing machines is available, which vary both in principle and design, but as only two or three types are used in any way extensively, only the more important of these latter types will be described in any detail.

TABLE No. 3.

Conversion Chart for Steels.

Tensile Strength. tons/sq. in.	Brinell Number 10 mm. ball 3000 K.G.M.	Vickers Number Diamond Pyramid.	Rockwell Number. 120° Diamond 150 Kgm. C. Scale.	Rockwell Number. $\frac{1}{16}''$ Ball 100 Kgm. B. Scale	Sclerosocope Number. Diamond Hammer.
24	105	105	—	58	17
26	114	114	—	63	18
28	123	123	—	68	19
30	131	131	—	72	20
32	140	140	0	76	21
34	149	149	5	80	22·5
36	158	158	9	83	24
38	168	168	12	86	25
40	178	178	15	89	26·5
42	188	188	18	91	28
44	198	198	20	93	29
46	208	208	22	96	30·5
48	218	218	24	98	32
50	228	228	26	100	33
52	240	240	28	—	34·5
54	249	249	29	—	36
56	258	258	31	—	37
58	267	267	33	—	38
60	276	276	34	—	39·5
62	285	285	35	—	41
64	294	294	36	—	42
66	303	303	37	—	43
68	312	314	38	—	44·5
70	321	325	39	—	46
75	345	355	42	—	49
80	368	383	44·5	—	52
85	392	413	46	—	55
90	413	436	48	—	58
95	435	465	49·5	—	61
100	460	496	52	—	64
110	503	552	55	—	70
120	550	620	58·5	—	76
130	595	685	61·5	—	82

The following gives a list of the better-known types of present-day hardness testing appliances :—

(*a*) Ball indentation testing machines.
(*b*) Pyramid indentation testing machines.
(*c*) Rebound testing apparatus.
(*e*) Scratch testing apparatus.

Of the above types of machines (*a*), (*b*) and (*c*) together cover practically the whole field of the hardness testing of metals and for this reason detail descriptions are confined to the most popular machines of these types.

6. BALL INDENTATION HARDNESS MACHINES.

This method of testing for hardness, which was developed by Brinell, consists in forcing a hardened steel ball into the surface of the material to be tested, the hardness of the material then being determined by the ratio—

$$\frac{\text{Load on steel ball}}{\text{Spherical area of indentation}}$$

The indent produced in the metal surface will in general range between one or other of the two types shown by Figs. 14 *a* and *b*, depending on the particular metal tested. Whilst there is no hard-and-fast rule, wrought materials generally give the (*a*) type of indent and cast metals the (*b*) type, but in either case it will be found that the contact surface determined from the dimension *d* is sharply defined and can be readily measured by means of a suitable microscope provided with a graduated eye-piece.

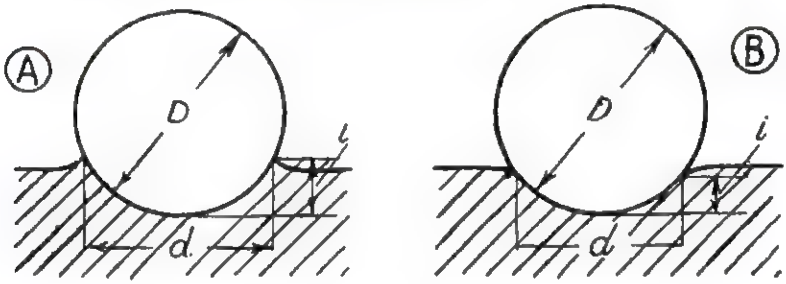


Fig. 14.

Employing the symbols used in Figs. 15 *a* and *b* :

$$\text{the hardness number} = \frac{\text{Pressure in kilograms P}}{\text{Spherical area of indent in sq. mms.}}$$

$$\text{or} \quad H = \frac{P}{1{\cdot}571\ D\ (D - \sqrt{D^2 - d^2})} = \frac{P}{\pi D i} \qquad (1)$$

It has been shown by Meyers that for similar indentations in similar materials the following law applies :—

$$\frac{P}{D^2} = \text{constant} \qquad (2)$$

Equations (1) and (2) give practically all the information which is necessary for ball indentation hardness testing.

The first equation enables the hardness number to be calculated for any values of load, ball diameter and indent diameter.

Where it is desired, as in the testing of thin materials, to employ a small diameter ball, equation (2) gives the load which is to be applied if the hardness numeral for the material is to be unaffected by the change.

In practice it is usual to employ a 10 mm. steel ball with a load of 2000 kgms., the spherical area of this indent being measured in sq. mms.

To facilitate the calculations only the diameter of the indent is measured and then by reference to tables prepared on the basis of a standard load and ball diameter the hardness number for the material is read off against the indent diameter.

Tables of Brinell hardness numbers applicable to the standard 10 mms. ball and various loads of 500, 1000, 1500 and 3000 kilograms are given by Table 4.

7. BRINELL TYPE MACHINE.

A wide variety of Brinell type machines are obtainable, but the original form employing oil pressure loading by means of a hand-pump is still the most popular.

Other types of machine employ either lever loading or dead-weight loading, which may be applied by hand-driven mechanisms or in isolated cases, where specially rapid testing is required, power-driven machines are employed.

The usual form of hand-operated, oil pressure machine, fitted with a 10 mm. indenting ball, is illustrated by the photograph, Fig. 15.

In this machine the oil pressure developed by a hand operated pump is supplied to a cylinder in which a steel ball is used as a piston, the load being read on a suitably calibrated gauge connected with the cylinder.

The load on the ball piston is transmitted *via* a short stiff rod to the 10 mm. ball, which produces the indent in the sample under test.

In order to ensure that the required load is not exceeded, a sensitive deadweight relief valve is connected in the system which lifts and bye-passes excess oil when the correct pressure is exceeded.

The value of the deadweight carried by the relief valve can be adjusted for various test pressures, these generally being fixed at 500, 1000, 1500, 2000 and 3000 kgms.

A sensitive pressure gauge calibrated to read the load on the ball is fitted to the apparatus ; this provides a very useful check on the smoothness of the pumping and considerably reduces the liability to over-loading and violent fluctuations of load.

Testing should always be carried out with the loading spindle perpendicular to the plane of the surface on which the impression

TABLE No. 4.
BRINELL HARDNESS NUMERALS.

D = Diam. of Impression in mms. H = Hardness Numeral.
For loads of 3000, 1500, 1000 and 500 kilograms.

D.	H.				D.	H.			
	3000	1500	1000	500		3000	1500	1000	500
2·4	653	326	218	109	4·8	156	78	51·9	25·9
2·5	601	300	200	100	4·9	149	74·5	49·6	24·8
2·6	555	278	185	92·6	5·0	143	71·5	47·5	23·8
2·7	514	257	171	85·7	5·1	137	68·5	45·5	22·8
2·8	477	238	159	79·6	5·2	131	65·5	43·7	21·8
2·9	444	222	148	74·1	5·3	126	63	41·9	20·9
3·0	415	208	138	69·1	5·4	121	60·5	40·2	20·1
3·1	388	194	129	64·6	5·5	116	58	38·6	19·3
3·2	363	182	121	60·5	5·6	111	55·5	37·1	18·6
3·3	341	170	114	56·8	5·7	107	53·5	35·7	17·8
3·4	321	161	107	53·4	5·8	103	51·5	34·3	17·2
3·5	302	151	101	50·3	5·9	99·2	49·6	33·1	16·5
3·6	285	143	94·9	47·5	6·0	95·5	47·8	31·8	15·9
3·7	269	135	89·7	44·9	6·1	92	46	30·7	15·3
3·8	255	128	84·9	42·4	6·2	88·7	44·4	29·6	14·8
3·9	241	120	80·4	40·2	6·3	85·5	42·7	28·5	14·2
4·0	229	115	76·3	38·1	6·4	82·5	41·3	27·5	13·7
4·1	217	109	72·4	36·2	6·5	79·6	39·8	26·5	13·3
4·2	207	103	68·8	34·4	6·6	76·8	38·4	25·5	12·8
4·3	197	98·5	65·5	32·8	6·7	74·1	37	24·7	12·4
4·4	187	93·5	62·4	31·2	6·8	71·6	35·8	23·9	11·9
4·5	179	89·5	59·5	29·8	6·9	69·1	34·6	23	11·5
4·6	170	85	56·8	28·4	7·0	66·8	33·4	22·3	11·1
4·7	163	81·5	54·3	27·1	—	—	—	—	—

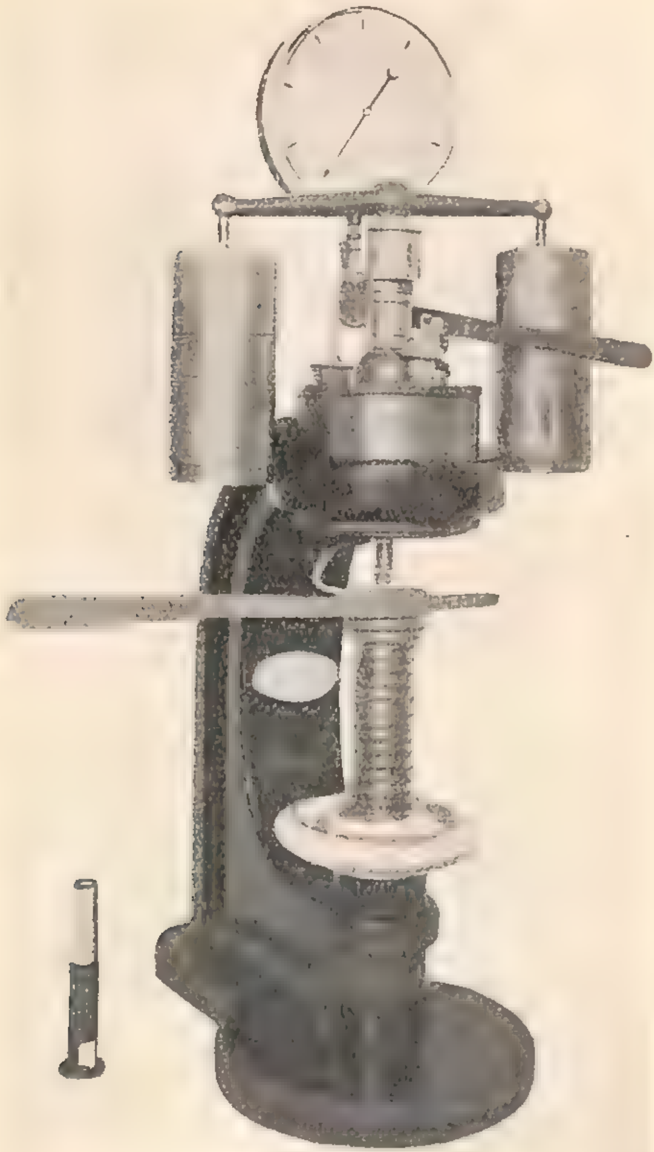


Fig. 15.

is to be made, and for the purpose of rapid adjustment the machine is provided with a spherically seated table capable of independent vertical adjustment by means of a screw-and-nut mechanism.

It is usual to leave the full load on the ball for a period of 15 seconds, in order to ensure that "give" of the material has taken place before the load is removed and the diameter of the impression measured.

To measure the diameter of the impression, the standard Brinell testing equipment includes a microscope with a magnifying power of about ten, in which a transparent scale reading in 0·1mm. is mounted in the eye-piece.

Special adjustments are provided for setting the eye-piece scale to correspond with an accurately scribed scale on which lines are set exactly 0·1 mm. apart.

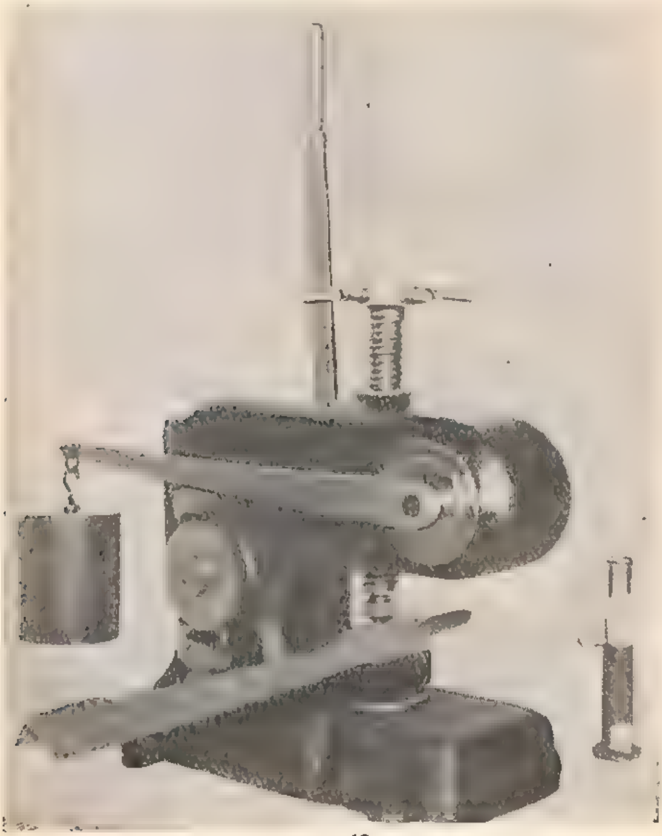


Fig. 16.

A mechanical lever-loaded type of Brinell machine, which is manufactured by Messrs. Brown Bailey's Ltd., is shown by the photograph, Fig. 16, and is generally known as the Johnson hardness tester.

8. PYRAMID INDENTATION HARDNESS MACHINES.

The principle on which this machine is based is very similar to that of the ball indentation machine, that is, the dimensions of the impression made in the material by the point of a pyramid-shaped tool under the action of a standard load are used to determine the hardness of the material against some convenient scale.

Most of the pyramid type of indentation machines have been designed to overcome one or more of the disadvantages which are associated with the ball machine, the most important of these being enumerated below :—

(1) Lack of similarity between impressions of different diameters made with the same ball.

(2) Limitations of ball type machines due to the deformation of the ball on very hard surfaces.

(3) The destruction of an appreciable area of the object, particularly on soft materials, by the use of ball tests.

With the pyramid-shaped indentation tool the impressions are similar no matter what their size, and the surface areas of different impressions are therefore proportional to the square of any corresponding linear dimensions.

The upper limit to which the ball test may be applied before excessive deformation of the ball occurs, varies with the type of steel employed for the manufacture of the balls and with their subsequent treatment.

At the best, however, it may be said that with the very best type of balls, which have been cold worked to increase their hardness, the upper limit to which they can be safely employed is 650-700 on the Brinell scale.

In order to overcome this drawback and increase the range of usefulness most of the pyramid testers are equipped with indentation tools made from diamonds ground to the pyramid shape and mounted in a metal cup. On account of the extreme hardness of the indenter, this type of machine is particularly suitable for testing hardened steels.

The small size of the diamond tool carries with it a further advantage in that under the necessarily lighter loads the impression made on the surface of the object is small and it therefore becomes possible to employ the test on certain classes of finished parts which would be damaged or destroyed by the use of the Brinell test, with its much larger impression.

Probably the most widely-known machines of this type are the Vickers' pyramid hardness testing machine and the Rockwell hardness testing machine.

The former, which is shown by the photograph, Fig. 17, employs as the indenting tool a square-based diamond pyramid, accurately ground to a facet angle of 136°.

Loading is applied to the indenter by means of a deadweight operating through a 20 - 1 leverage system. The rate of loading is controlled by a cam-and-dash pot mechanism and is consequently independent of the operator. Resetting the indenter for a second test is readily carried out by depressing the foot pedal.

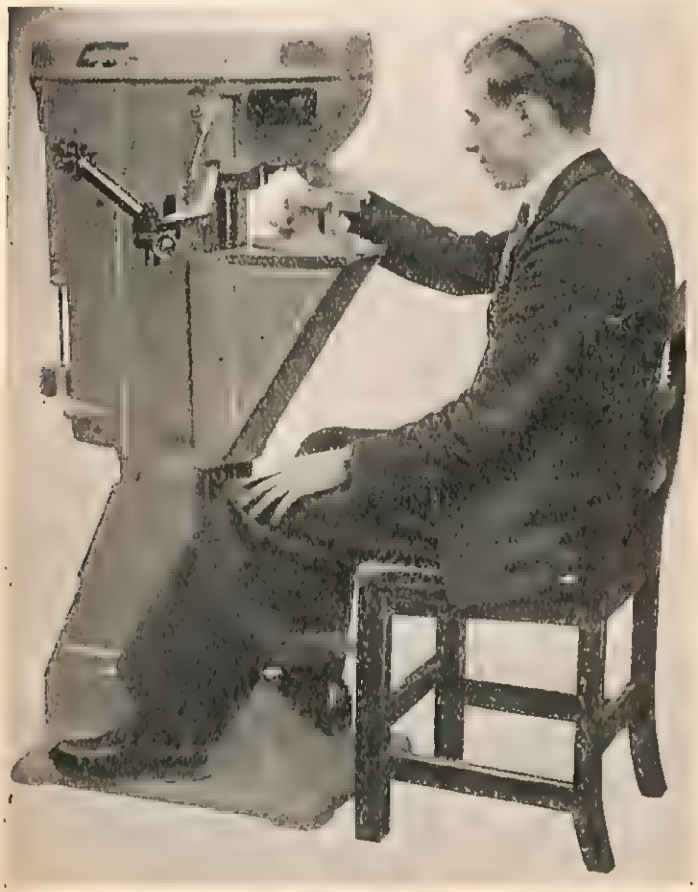


Fig. 17.

Measurement of the impression is made across a diagonal by means of a special microscope fitted with an eye-piece containing knife edges, which can be adjusted by rotating a thumb screw.

The distance between the knife edges when set to the diagonal is automatically recorded and by reference to the tables supplied with the machine the hardness numeral can be read off correspondingly with this figure.

As with the Brinell test the hardness value is calculated from the relation :—

$$\text{Hardness Numeral} = \frac{\text{Load}}{\text{Impressed Area}} = \frac{\text{Load}}{\text{Constant X (Diag'l)}^2}$$

The Rockwell hardness testing machine also employs a diamond indenter, but in this case it is ground to the form of a cone of 120° included angle.

Measurement of the impression is not carried out in the usual manner by means of a microscope, but the machine is provided with a sensitive dial-type depth gauge, which records automatically and is conveniently calibrated to read hardness numerals directly.

As the gauge actually records the downward movement of the indenter, it is important to eliminate "give" in the supporting arrangement for the specimen. This end is achieved by applying the test load in two stages, first the "minor load" is applied to take up the "give" and the recording gauge then set to zero, the "major" or full load is then released and the reading taken on the assumption that no further "give" occurs under the heavier load.

The Rockwell hardness machine employs a special scale of hardness numerals, which have no direct relation to other hardness scales or to the usual relation of load divided by impressed area.

Both the Vickers and Rockwell machines are provided with small steel ball indenters and can therefore be used for carrying out the Brinell type of hardness test. On account of the comparatively light load and to the small size of ball employed with these machines, the damage to the surface of the specimen is very slight, and satisfactory tests can thus be made on thin sheet material impossible to test with the standard Brinell machine.

9. REBOUND HARDNESS TESTERS.

The only instrument of this type which has achieved any extensive use is the Shore scleroscope, shown by the photograph, Fig. 18.

This apparatus consists essentially of a small diamond tipped cylinder, weighing about $\frac{1}{12}$-ounce, which is dropped a distance of 10″ on to the surface to be tested.

On striking the surface a small indent is made, the size depending on the hardness of the material, and the hammer rebounds. If the

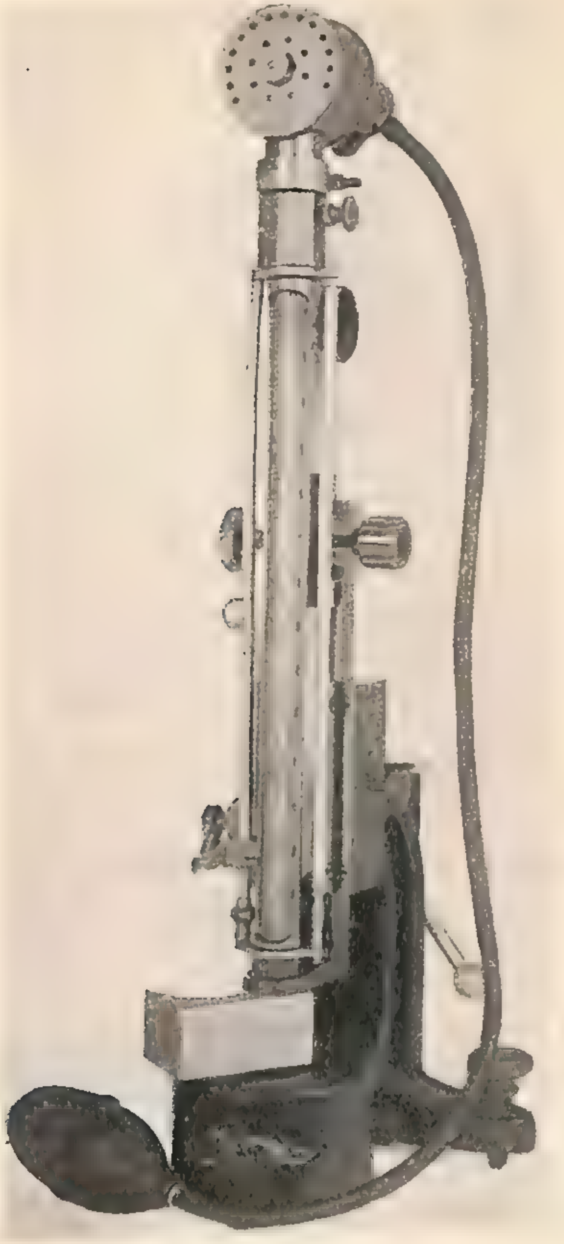


Fig. 18.

surface were perfectly hard and elastic the hammer would rebound to practically its original height of 10″ and no permanent indent would remain in the surface.

In practice, however, even the hardest of materials are left with a small permanent impression, indicating that energy has been absorbed from the hammer, which consequently never quite reaches its starting position on rebounding.

As will be evident from the photograph, the diamond-tipped cylinder is contained in a glass tube provided with a graduated scale reading from 0 at the bottom to 140 at the top.

The small cylinder is raised to the top of the glass tube by air suction provided by means of a rubber ball, connected to the upper end of the glass tube. On reaching the top of the tube the cylinder is held by a small clip and is then released to fall on the test surface by squeezing the rubber ball. By careful observation the height of the rebound is noted against the scale, which gives a direct hardness reading in shore units, these units being selected so that the hardest of steels would give a reading of approximately 100 units.

The instrument is particularly suited for the testing of small hardened steel parts, but can also be used for any class of steel or non-ferrous metal, provided a smooth surface is available and the object is rigidly supported.

For the softer materials a steel-tipped cylinder is supplied, which is known as the "magnifier hammer." Because of its rounded striking point this cylinder has less penetration into the soft materials and therefore rebounds to a greater height than would the diamond tipped cylinder.

A special scale of hardness numbers is used with the magnifier hammer which, being rarely employed except for non-ferrous metals, is not included in Table No. 2.

10. HARDNESS TESTS ON LARGE FORGINGS, Etc.

In works concerned with the manufacture of large machinery it frequently occurs that hardness tests are required on parts too big to be accommodated in the gap provided in the normal hardness testing machines.

For cases of this kind, Brinell type machines can be obtained which are built into the bridge of a rectangular steel frame capable of accommodating castings or forgings of considerable size. Machines of this type are manufactured by J. W. Jackman & Co., of London, and by the Tinius Olsen Co., Ltd. (Agents, Ed. G. Herbert Ltd., Manchester).

This type of apparatus, however, is generally limited in its scope to parts of convenient symmetrical shape, such as barrel or disc types of rotors, large shafts, rings, etc., and cannot be regarded as

having a universal application. Further, such equipment is not readily portable and would need to be served by a crane or runway, by which the parts to be tested could be carried to the machine.

In large works this procedure may entail transporting heavy parts considerable distances, with the consequent loss of time and interference with production arrangements.

To meet the general works requirements for hardness tests on large parts or as a supplement to the equipment described above special forms of portable apparatus have been developed.

One type of such apparatus marketed by the Sheffield Testing Works consists of a calibrated steel ring with load-recording device. To carry out tests a steel ball is secured to the outer periphery of the ring and with this ball resting on the surface to be tested, load is gradually applied to the opposite side of the ring by any convenient means, until the dial records the load appropriate to the size of ball employed.

Measurement of the resulting impression and the determination of the hardness numeral is then exactly as for the Brinell test.

A further popular type of apparatus is shown by the photograph Fig. 19, which illustrates the "Poldi" Hand Brinell Tester, marketed by Alfred Herbert, Ltd., Coventry. This apparatus consists essentially of a punch A, resting on a standard bar B, which in turn is supported on a 10 mm. ball C.

To carry out a test, the ball is held against the surface to be tested S, and the punch A then struck sharply with a hammer. This results in two impressions being formed by the ball, one in the surface S and the other in the standard bar B.

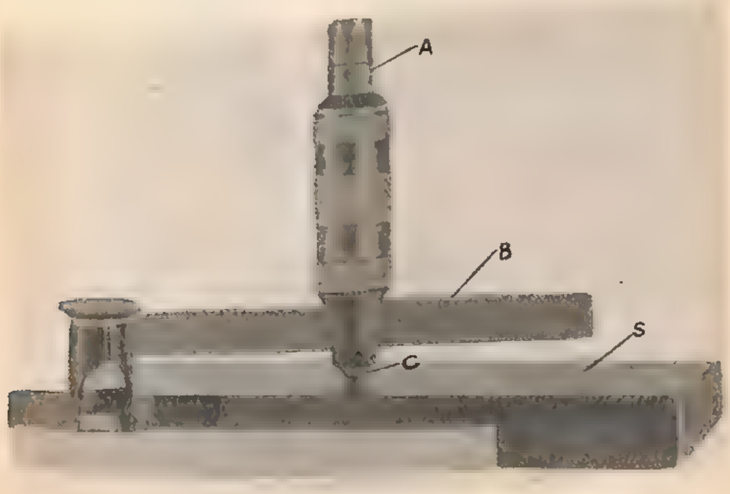


Fig. 19.

The hardness of the material under test is then estimated as follows :—

H = Brinell hardness of standard bar.
d = diameter of impression in standard bar.
D = diameter of impression in material under test.

Then hardness of material = $H \times \left(\frac{d}{D}\right)^2$ (approximately).

It is important when using this form of test to employ a standard bar which does not differ appreciably in hardness from the material under test. For this reason it is usual to keep a selection of bars of various degrees of hardness.

IMPACT TESTS.

For many duties the capacity of a material to resist shock is only of secondary importance. There are, however, a number of important services, such as chains, carriage and wagon couplings, etc., where structures are required to withstand without injury or failure sudden applications of load of the nature of impact forces. In such cases a high impact resistance is of primary importance.

It was at one time believed that the impact resistance of a steel could be estimated from the properties determined by the tensile test, but such a connection between the two sets of properties has now been conclusively disproved, and for certain services impact tests have come to be regarded as essential. Investigation has now shown that it is possible by suitable heat treatments to put the same material into two different conditions, both having the same tensile properties, but differing widely in impact resistance.

A typical example of such a case is given below for a nickel chrome steel.

	Yield Point. tons/sq."	Tensile Strength. tons/sq."	Elongation. %	Red. of Area. %	Izod Impact ft. lbs.
Before treatment,	56	62·9	24	64	59
After treatment (400°C.—7 days)	55·4	63·0	22·8	59	13

Failures in service caused by shock generally occur at positions where, due to sharp fillets or notches, the volume of material subjected to the maximum strains is small and extremely localised.

Under these conditions the capacity of the structure to absorb energy without failure is small, as the externally applied energy is concentrated into a small zone and very high local stresses result.

Different classes of steel or the same steel differently heat treated may have widely ranging resistance to impact forces.

In order to estimate the inherent capacity of such materials to resist shocks a method of test known as the notched bar impact test has been devised, by means of which standard-sized specimens

provided with notches are subjected to impact forces in a machine capable of recording the energy absorbed during fracture of the specimen across a notch.

A number of accepted forms of the test are in common use, of which the best known are tabulated below :—

Type and Capacity of Machine.		*Type and Size of Specimens.*
1. Izod.	Pendulum—120 ft. lbs.	Cantilever, 10 mm. × 10 mm. × 75 mm.
2. Charpy.	„ —30 kg. m.	Beam, 10 mm. × 10 mm. × 60 mm.
3. Guillery.	Flywheel —60 kg. m.	„ „ „ „
4. Fremont.	Falling Tup—20 or 60 kg. m.	„ „ „

Note.—Alternative sizes and shapes of specimen are referred to later.

Probably the most widely-used of the above forms of test are the Izod and Charpy, both of which are of the pendulum type. With these two types of machine the striking energy is derived from the heavy bob of a simple pendulum swinging on knife edge supports.

The pendulum bob, which is made of steel or cast iron, is provided with a hardened steel striking edge so arranged that it strikes and breaks the specimen across its notch when the bob is moving with maximum velocity at the bottom of its swing.

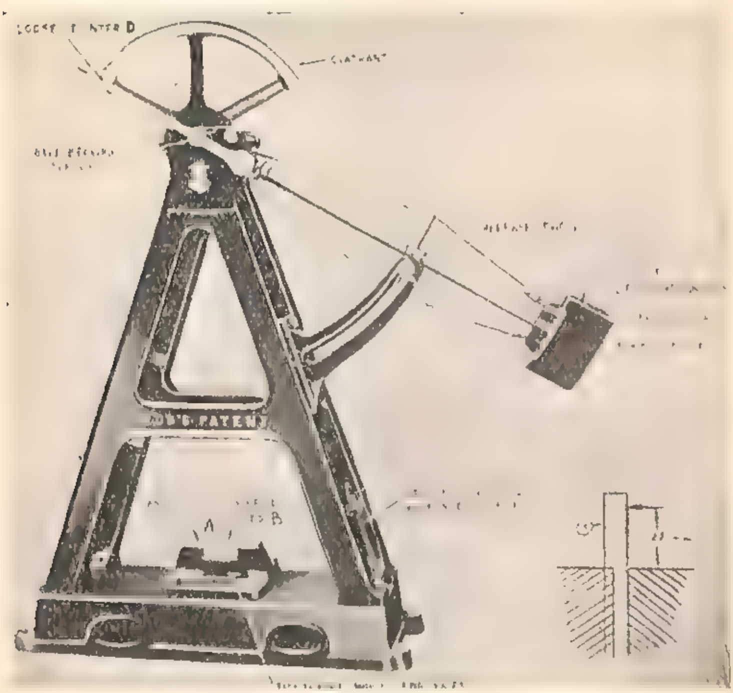


Fig. 20.

11. IZOD TEST.

The usual form of Izod machine of 120 ft./lbs. capacity, as made by Messrs. Avery Ltd., is shown by Fig. 20.

Referring to this illustration, the specimen A is gripped by the dies B, so that the centre of the notch is level with the surface of the dies.

The pendulum bob C is then released from its deflected position and swings down towards the specimen, the striking edge making contact at a position 22 mm. above the notch.

After breaking the specimen, the pendulum swings on, carrying with it the pointer D, which is left at its extreme position after the pendulum returns.

By means of a suitably calibrated scale the pointer can be made to read the loss of energy by the pendulum, *i.e.*, the energy absorbed in breaking the specimen.

Standard Izod machines have a maximum energy capacity of 120 ft./lbs. at a striking velocity of 13·87 ft. sec., this being found capable of fracturing the toughest classes of steel or non-ferrous metals.

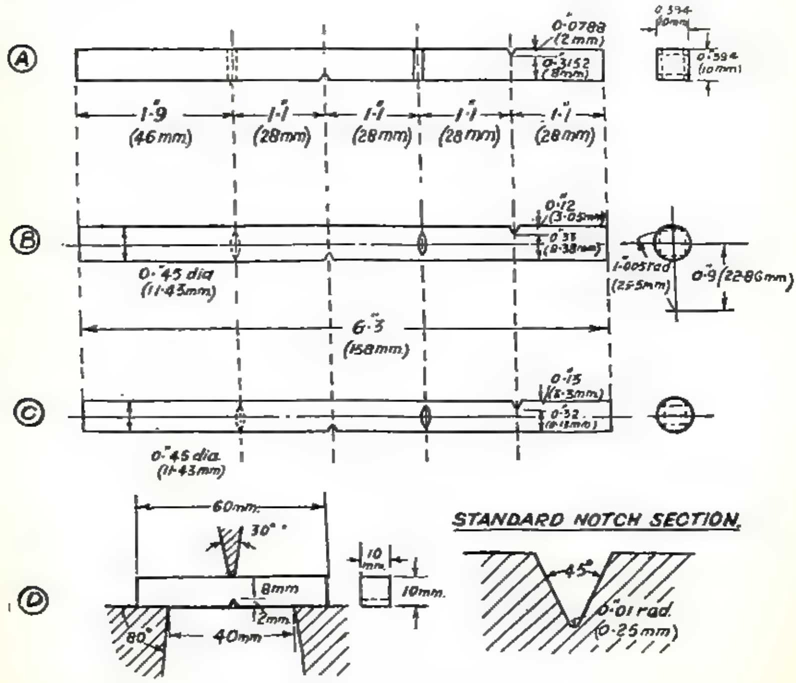


Fig. 21.

The usual size of Izod specimen is shown by diagram A on Fig. 22, which gives the dimensions for the notch and shows four notches arranged one on each face of the specimen.

It may be observed that where, owing to limitations of material it is not possible to obtain the full 10 mm. in one direction, tests can still be made by cutting the notch across the narrow face and taking the breaking energy as being proportional to the diminished width, provided this is not less than 5 mm. The result can be given in terms of the standard specimen after a suitable correction for width.

Two other types of Izod specimens, which are becoming popular on account of their comparatively cheap cost, are shown by B and C, Fig. 21. These consist of turned specimens provided with either turned or milled notches.

For convenience, the dimensions of these specimens have been adjusted in order to give results similar to those obtained with the normal size of specimen and these specimens are now accepted by many important inspecting authorities.

In special cases, other sizes of specimen are occasionally employed, but in such tests checks are usually made on similarly shaped specimens taken from a material whose impact characteristics are known.

12. CHARPY TEST.

The Charpy machine, shown in Fig. 22, is very similar in principle to the Izod machine, the source of energy being obtained from the heavy bob of a swinging pendulum, which in the same manner as the Izod pendulum carries a light pointer to its extreme position and records the energy absorbed in breaking the specimen.

The main difference occurs in the type and method of supporting the specimen, which in the Charpy test takes the form of a small beam held near its ends against two hardened steel blocks spaced 40 mm. apart, as shown by the sketch D, Fig. 21.

When testing, the notched face of the specimen is placed against the supports with the notch midway between them.

Specimens are usually made 60 mm. long and 10 mm. × 10 mm. in section, the single notch of the same shape as the Izod notch being cut across the centre of one of the faces.

Only one test can be made on the same specimen and it is necessary to make a number of similar specimens if it is desired to carry out tests in more than one direction.

As with the Izod test, other sizes of specimen may be tested in the Charpy machine, suitable corrections being made to the results to bring them into line with the standard specimens.

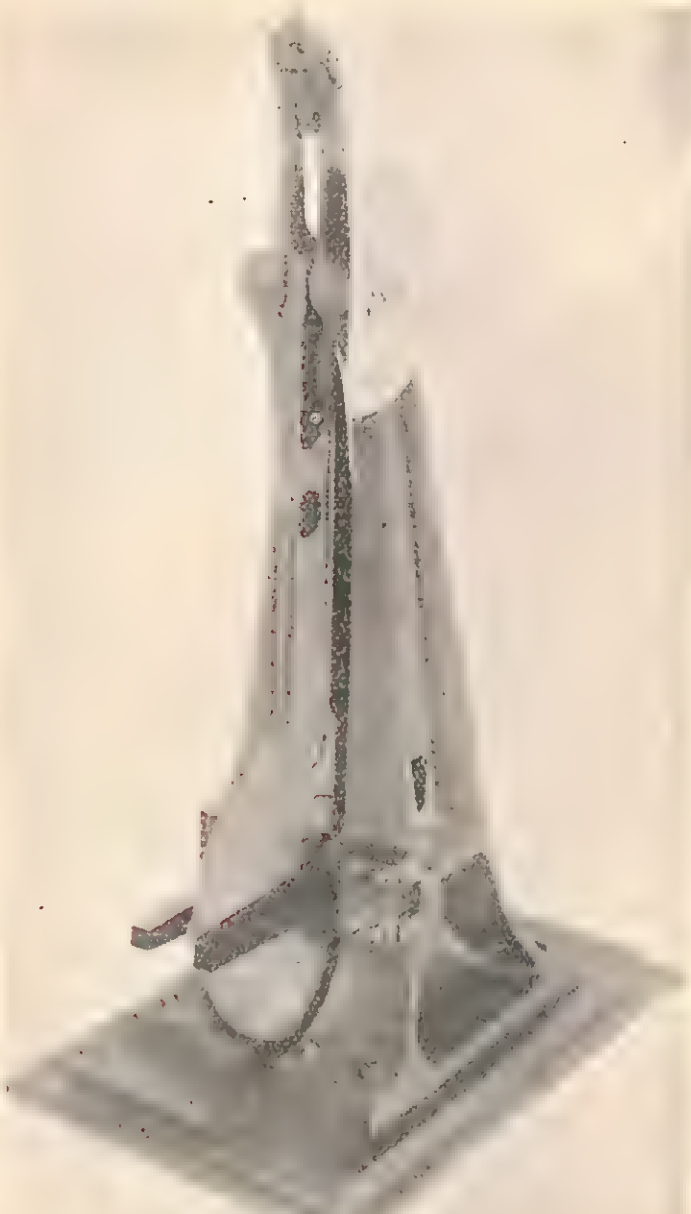


Fig. 22.

13. OTHER IMPACT MACHINES.

As the vast majority of impact testings is carried out using either the Izod or Charpy machines, little need be said concerning other types of test, except that the standard 10 mm. square specimens with the usual shape of vee notch are generally employed, so that results are directly comparable with Izod and Charpy tests.

14. IMPACT RESISTANCE OF COMMON STEELS.

For convenient reference the normal Izod impact values obtained on standard specimens are listed below for a selection of the more usual present-day structural steels.

It should be noted that specifications generally quote figures considerably less than those given in the list. This is done in order to allow a practical margin to cover commercial variations in material and directional effects in forgings, etc.

Material.	*Impact (ft./lbs.)*
0·15% C. steel forged and normalised, ...	80
0·4% C. " " " ...	30
40 ton 5% nickel steel, OH and T, ...	70
0·1% C. stainless steel (13% Cr.), OH and T,	65
0·27% C. " " " ...	35
60 ton nickel chrome moly. steel, OH and T,	50

TRANSVERSE TESTS ON CAST IRON.

In view of the brittle character of cast-iron, which constitutes one of its chief disadvantages, it has now become usual as a supplement to the tensile test to assess the quality of a cast-iron in terms of its resistance to fracture under bending loads.

This type of test is known as the transverse test and consists in submitting a uniform sample bar of the cast material to a bending test, during which the breaking load and the deflection just prior to fracture are measured.

The standard tests employ a round or square section bar, cast in one with the job and broken off after removal of the casting from the mould.

During test the bar rests freely on two rounded supports spaced at a fixed distance apart, loading being applied at the centre of the span through the medium of a radiused tool.

The load can be applied and measured by means of the usual type of tensile machine or by special equipment. Deflection at the centre of the bar is recorded on a dial indicator located immediately below the point of application of the load.

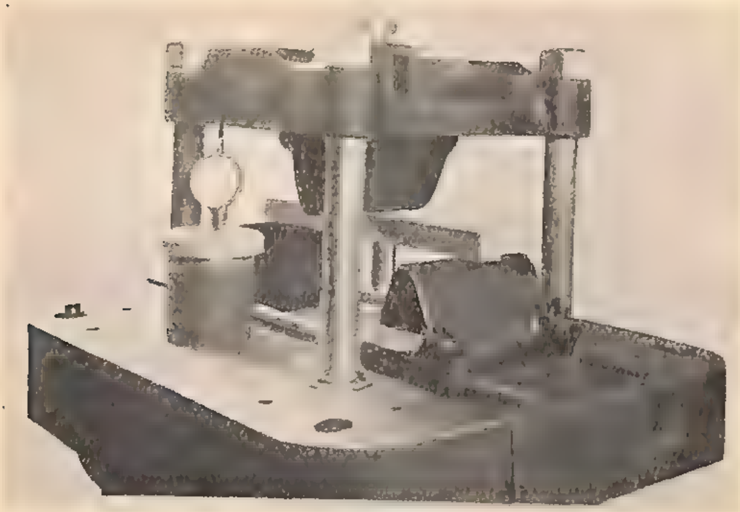


Fig. 23.

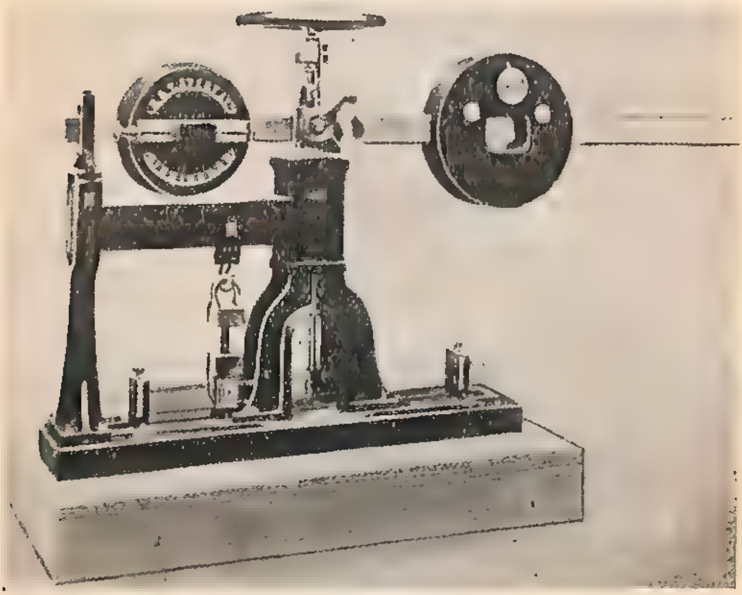


Fig. 24.

15. TRANSVERSE TESTING EQUIPMENT.

In cases where a tensile machine with facilities for compression testing is available, it is only necessary to provide suitably spaced supports with a central loading tool and measuring device in order to carry out transverse tests.

Such an arrangement is depicted in the photograph, Fig. 23, which shows a 1″ square specimen supported on the table of a testing machine over a span of 12″ and loaded at its centre.

A number of machines specially designed for tensile and transverse tests on cast-iron are obtainable ; these are generally provided with hand-operated screw loading and are essentially tensile machines in miniature.

One type of this machine manufactured by Messrs. Avery Ltd. is shown by the photograph, Fig. 24.

16. TRANSVERSE TEST SPECIMENS.

Transverse test specimens are generally cast to size and where practicable are attached by one end to the casting which they represent ; they may also at other times be cast separately from the same ladle of metal which is used for the casting.

A number of standard specimens are in common use, some employing square section bars, whilst others are made circular in section of a diameter determined by the average thickness of the castings which they represent.

The usual sizes of transverse bars are given in the following table, together with typical specification figures for best quality grey cast-iron.

SQUARE SECTION TRANSVERSE SPECIMEN.

Length	Section	Test Span	Breaking Load.	Deflection at centre of span.
ins.	ins.	ins.	lbs.	
14	1 × 1	12	2,688	0·075″ min.

CIRCULAR SECTION TRANSVERSE SPECIMEN.

Average Thickness Casting.	Length	Diam.	Test Span	Breaking Load	Defln. at centre of span.
ins.	ins.	ins.	ins.	lbs.	
¾ max.	15	0·875	12	1,185	0·12″
¾ to 2	21	1·2	18	1·954	0·15″
Over 2	21	2·2	18	10,000	0·12″

17. CORRECTIONS FOR NON-STANDARD TRANSVERSE SPECIMENS.

Transverse specimens are usually tested in the "as-cast" condition, and although generally of uniform cross-section from end to end, different specimens may vary appreciably in actual dimensions from one another.

In order to correct for such differences and to obtain the results in terms of the standard specimens, the simple formulae given below are employed

(*a*) **Square Section Specimens**, where

$B'' =$ breadth and $D'' =$ depth of actual transverse specimen.

Equivalent breaking load on $1'' \times 1''$ specimen

$$= \frac{\text{Actual breaking load}}{BD^2}$$

Equivalent deflection on $1'' \times 1''$ specimen
= actual deflection $\times$ D.

(*b*) **Round Section Specimens**, where—

	Standard Specimen.	Actual Specimen.
Diameter	D	D_1
Breaking load ...	W	W_1
Deflection	δ	δ_1

Then, Equivalent breaking load on standard $= W = W_1 \left(\frac{D}{D_1}\right)^3$

and Equivalent deflection on standard $= \delta = \frac{D_1}{D}\,\delta_1$

FATIGUE TESTS.

Fatigue in metals results in the formation of a slow-spreading fracture, which frequently has the clean-cut but waved appearance associated with the fracture of glass, although occasionally bearing a similarity to the fine granular fracture of cast-iron.

The effect of the surface condition of a metal on its fatigue resistance can be important and a considerable amount of work has been done on this subject by a number of investigators, both in this country and in the U.S.A.

In the author's experience it would appear that whilst differences in machine finishes may have importance with thin steel sections, these differences generally become negligible for sectional thicknesses greater than $\frac{3}{8}''$.

There is also evidence that the fatigue resistance of specimens in the condition as left following heat treatment is much improved,

even on $\frac{3}{8}''$ thick sections, by machining away 0.01″ of the surface layer.

Improvement in fatigue resistance can generally be obtained by shot peening with a blast of hard steel shot.

The occurrence of fatigue failures in rotating and reciprocating machinery has no doubt been observed right from the inception of such structures, but these fractures were probably in the majority of cases completely misinterpreted by the early engineers. Traces of the original beliefs are still occasionally heard when typical fatigue fractures are described as the results of brittleness or of crystallisation of the material.

These early misconceptions of the cause of fatigue failures are readily understandable, in view of the complete absence of any evidence of ductility in the fracture and also as noted above in the similarity of many fatigue fractures to the conchoidal fracture of glass or to the "short" granular fracture of cast-iron.

It is important, however, to note that all granular fractures are by no means necessarily the result of fatigue, but may often be correctly ascribed to brittleness of the material resulting from incorrect heat treatment or for other reasons.

18. FATIGUE RESISTANCE.

Fatigue failure is caused by excessive alternations of stress, resulting either from an initially faulty design or to the presence of extreme vibrations for which no provision could be made.

Under fixed operating conditions the fatigue resistance of most ferrous metals is a definite quantity, which is expressed as the range of alternating stress, which will just not produce failure no matter how long the stress alternations persist, or is described shortly as "The Limiting Safe Range of Stress."

Exposure to stress alternations less than this value will give indefinitely prolonged safety, but if the range is greater than this limiting figure the life of the material will be limited and will become progressively shorter as the stress range is increased.

Such alternations of stress may take place about zero as a mean stress, or the mean stress may be of any value either tensile or compressive within the capacity of the material. The range of safe alternations of stress is, however, governed by the value of this mean stress, and it is important that correct allowance be made for it.

The connection between the life of a member, defined by the number of stress alternations to cause failure, and the stress-range imposed will be made clear by the curved line AB on the diagram Fig. 25A, which also indicates graphically what is meant by the "Limiting Safe Range of Stress."

In case of non-ferrous metals it is generally found that the value of the alternating stress shich will just not produce failure

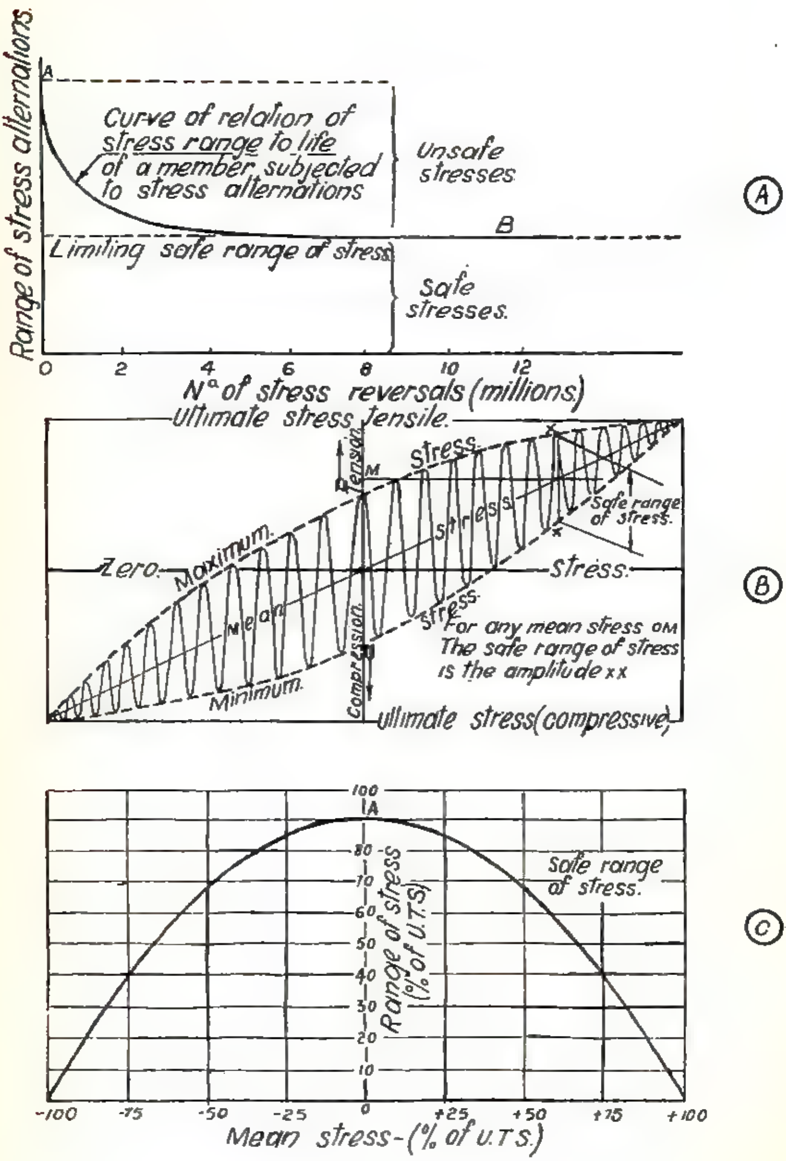

Range of stress alternations.
A
Curve of relation of stress range to life of a member subjected to stress alternations
Unsafe stresses
(A)
B
Limiting safe range of stress
Safe stresses.
0
2
4
6
8
10
12
Nº of stress reversals (millions)
Ultimate stress tensile.
Tension.
M
Stress.
x
Safe range of stress.
Maximum.
stress
Zero.
Stress.
(B)
Mean
Stress.
For any mean stress OM The safe range of stress is the amplitude xx
compression.
Minimum.
ultimate stress (compressive)
100
A
80
70
60
50
40
30
20
10
Range of stress (% of U.T.S.)
Safe range of stress.
(C)
-100
-75
-50
-25
0
+25
+50
+75
+100
Mean stress-(% of U.T.S.)

Fig. 25.

depends on the number of applications of the stress. The limiting safe stress becomes progressively smaller as the number of stress cycles is increased.

When specifying a fatigue limit for such metals it is advisable also to specify the number of stress cycles on which the limit is based. This qualification for non-ferrous metals should be understood to apply throughout the sections dealing with fatigue.

19. RELATION OF FATIGUE TO TENSILE STRENGTH.

There appears at present to be no scientific reason for relating the fatigue strength of a metal to its tensile strength and it should be understood that, although these quantities are both fixed for a given material and so lead to a definite numerical ratio between them, this is merely employed as a convenience and has little importance otherwise.

Most investigators of fatigue in metals have expressed their results as a fraction or as a percentage of the tensile strength, in addition to the more logical method of presenting them in terms of the Limiting Safe Range of Stress. No matter which procedure is employed, the value of the mean stress at which the results were obtained should always be stated.

A short list, including the usual engineering materials, of the approximate values for the percentage ratio—

$$\frac{\text{Limiting Safe Range of Stress}}{\text{Ultimate Tensile Strength}} \times 100$$

when the mean stress is zero are given in the table below :

Carbon steels (0 to 0·2% of carbon)	Ratio	=	100%
Carbon steels (0·2% to 1·0% carbon)	,,	=	90%
Alloy steels (not including tool steels)	,,	=	90%
Non-ferrous metals	,,	=	60%

The above values should be regarded as only rough guides to assist in preliminary designs, the more c omplete data relating to particular materials and the effect of various heat treatments can in most cases be obtained from the extensive literature on the subject.

These ratios or percentages will be reduced for any value of the mean stress other than zero, no matter whether the mean stress be tensile or compressive ; this effect is diagrammatically illustrated by Fig. 25B, in which the sine waves are drawn to indicate the presence of alternating stresses.

The actual value of the ratio for a given mean stress can only be determined accurately by an actual test, but based on the results of a large number of such tests, Gerber has suggested what is known as the "Parabolic Law," by means of which it is possible to form an approximate estimate of the safe range of stress alternations for

any value of the mean stress, provided the safe range is known when the mean stress is zero.

Gerber's Parabolic Law is illustrated graphically by the diagram, Fig. 25c, in which the ordinate is the "Range of Stress" and the abscissa is the "Mean Stress," both being expressed as a percentage of the ultimate stress.

The method employed is to mark the point A on the zero ordinate such that OA (in this case taken as 90%) is the safe range of stress when the mean stress is zero.

A parabola is then drawn through the three points A (the apex) and the two extreme points on the base at +100% and −100%.

This curve then defines the safe range of stress alternations for any value of the mean stress between the ultimate stresses in tension or compression.

As an example, the diagram shows by the dotted line that for a mean compressive stress of 50% of the ultimate, the safe range of stress alternations is 68% of the ultimate strength.

Similar parabolas may be drawn for any other value of the safe range OA, this ordinate OA being the one most readily determined in practice, as the majority of fatigue testing machines are designed to give the limiting value of the safe range of stress when the mean stress is at zero.

20. CORROSION FATIGUE.

The effect of corrosive action on the fatigue resistance of metals, even though the attack is very mild when judged from ordinary standards, is in most cases very marked.

It has been demonstrated that running ordinary tap water over steel specimens undergoing fatigue tests will reduce the resistance of the material by more than 50%.

This effect is due possibly to the high local stress concentrations which occur in the neighbourhood of the small pits developed under the corrosive action.

As a rough general rule, which applies to most steels and many non-ferrous metals and alloys, it may be taken that the presence of corrosive action will reduce the safe range of stress alternations to one-half or less of the safe range in dry air.

21. FATIGUE TESTING MACHINES.

Fatigue failure may in practice result from (*a*) alternations of direct stress, (*b*) alternations of bending stresses, or (*c*) alternations of torsional stresses (shear).

Fatigue may also result from a combination of two or more of the above actions and important work on this subject has been carried out in this country by Gough and Pollard.

The subject of fatigue in metals, following on the discovery of its causes and the general tendency to higher running speeds in machinery, has during the last twenty years attracted much attention and has led to the production of a range of testing machines adapted for direct, bending or torsional fatigue tests.

It is probable that the greatest number of fatigue failures are due to reversed bending stresses and for this reason, together with the comparative simplicity of the equipment, this type of testing machine is by far the most popular type.

Such machines, however, have an important limitation, in that it is only possible to subject the surface layer of material to the maximum alternations of stress. This fact really provides the main justification for the more complicated direct stress machine.

In view of the comparative rarity of torsional fatigue failures, the torsional fatigue machine has not received the attention given to other types of fatigue apparatus and in consequence fewer machines of this type have been developed.

22. DIRECT STRESS FATIGUE MACHINES.

Although a number of machines have been developed which are capable of applying alternations of direct stress, these have generally received a very localised attention and only the Haigh type of machine, shown by the photograph and diagram, Fig. 26, has achieved any extensive use.

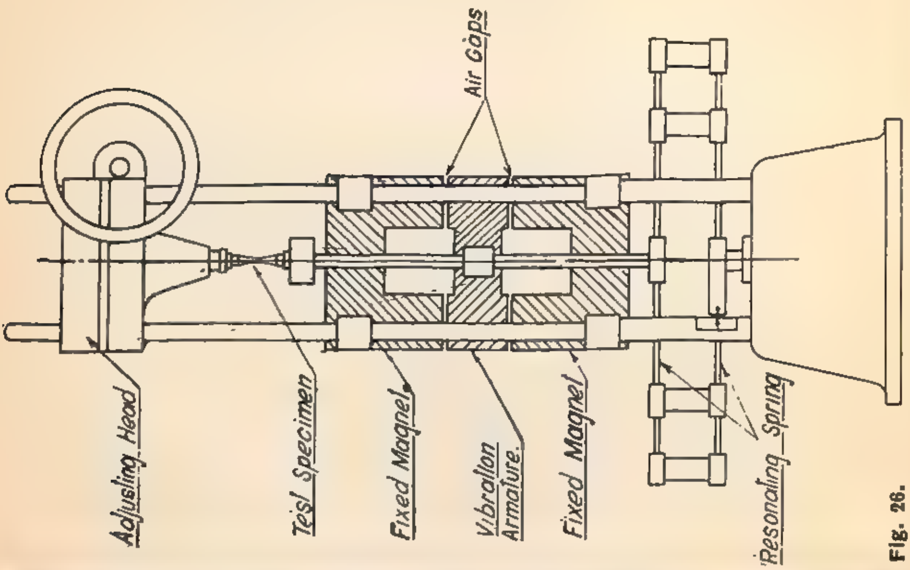
This machine is constructed to apply any given range of alternating direct stress to the specimen and is provided with adjustments for setting the mean stress to the desired value.

The load impulses are derived from electro-magnets supplied with alternating current, from a special generator. In order to obtain the maximum effect from the magnets, the lower specimen grip is spring-supported and tuned to resonance with the magnetic impulses before insertion of the specimen.

23. BENDING STRESS FATIGUE MACHINES.

(A) **Rotating Type.**—The rotating type of fatigue machine, in which the specimen is subjected to bending stresses which reverse due to its rotation, is on account of its comparative simplicity and its approximation of the conditions obtaining in rotating shafts the most widely used of all forms of fatigue test.

With this method of testing, the specimen, which is turned to a standard shape, is subjected to a bending moment acting always in the same plane and therefore producing a state of tension on one side of the horizontal diametral plane and compression on the other.


Air Gaps
Adjusting Head
Test Specimen
Fixed Magnet
Vibration Armature.
Fixed Magnet
Resonating Spring

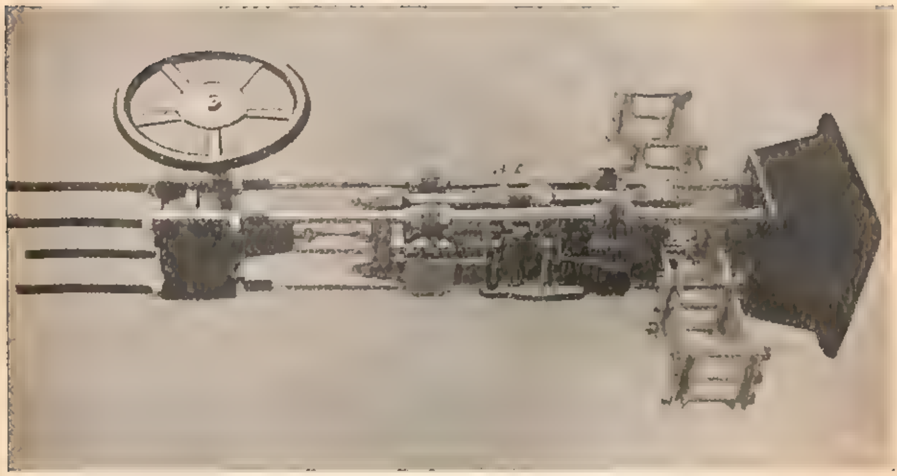


Fig. 26.

The specimen, which is supported in suitable bearings, is motor driven and being, therefore, under the action of the unidirectional bending moment is subjected at all points except its neutral axis to cyclic reversals of stress synchronising with its rotation, the stresses being of course a maximum in the surface material.

Such a machine, in which the specimen takes the form of a cantilever with the load applied at the free-end through the medium of a ball race, was first introduced by Wöhler and is now generally known by the name of its originator.

A typical machine of this type is shown by the photograph, Fig. 27, which also includes a sketch of an improved form of specimen in which the maximum stress occurs at a position along the tapered portion, well removed from the end radii.

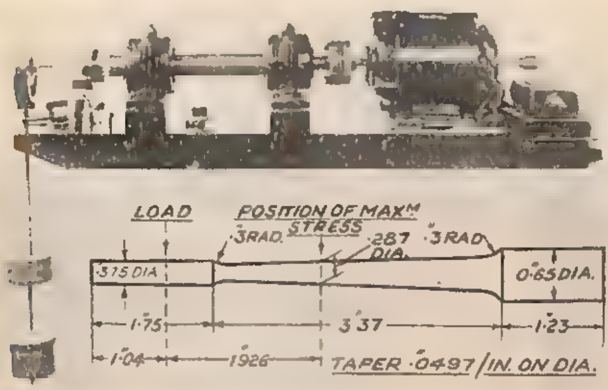


Fig. 27.

Other types of rotating machine have been developed in which the specimen is supported in bearings at both ends, the central test length then being subjected to a uniform bending moment. This type of apparatus has advantages over the cantilever type, owing to the greater length of specimen surface which is exposed to the maximum stress and also to its ability to restrict the most highly stressed region to a uniformly parallel length without the complicating effect of the root radius met with in the case of the cantilever test.

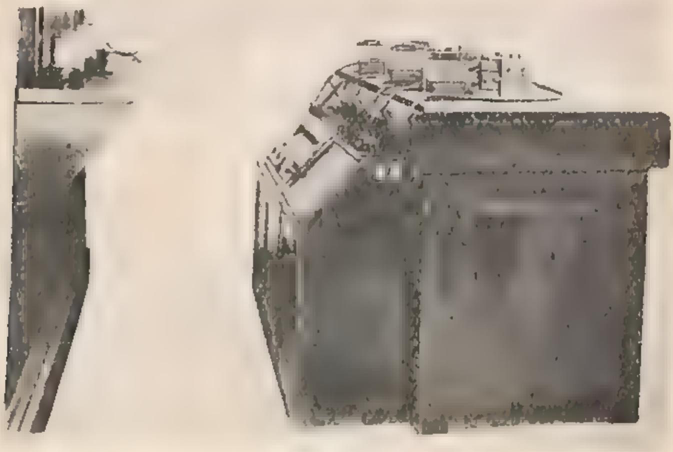
(B) Reciprocating Type.—One of the principal disadvantages of the direct stress and rotating types of machine is that these machines confine the tests to specimens which have been turned to a standard shape and in consequence the scope of the apparatus is practically limited to tests of materials.

It is frequently desirable, however, to test small machine parts in their finished condition, in order to determine the effect on their fatigue resistance of changes in the process of manufacture or of modifications in the form of the part.

Machines capable of carrying out this kind of work in addition to the usual measurements have been developed. One such device applies controlled magnetic impulses to the part or specimen mounted in a manner which closely reproduces its service conditions.

The machine maintains the specimen in vibration by magnetic impulses which synchronise with its natural vibration frequency and therefore enables large amplitudes or the equivalent in stress to be maintained with comparatively little expenditure of energy.

Examples of such equipment developed by the author are shown by the photographs, Figs. Nos. 28 and 29.



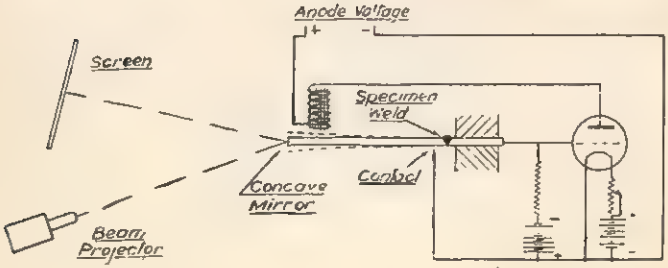


Fig. 28.

Fig. No. 28, a three-unit installation, includes the circuit diagram and indicates the principle on which the apparatus works. Apart from carrying out fatigue tests on small machine parts, welded joints, etc., this apparatus was designed for the measurement of vibration frequency and includes a stroboscopic device (not shown) for this purpose.

The illustration, Fig. No. 29, shows a more recent and improved battery of twelve moving coil type fatigue machines designed to operate at the natural frequency of the coupled system and provided with arrangements for enclosing the test specimen in an electric furnace for tests at high temperature. The circuit arrangement is different from that of Fig. No. 28, as the impulse control is in this case by means of a variable frequency electronic oscillator.

A number of other reciprocating fatigue machines have been employed by different investigators, some of them magnetically operated and others by means of adjustable cams or other mechanical devices. These latter machines, however, are generally limited to tests upon specially prepared samples and not being so generally convenient as the Wöhler type of machine have little to recommend them.

24. TORSIONAL FATIGUE MACHINES.

A variety of ingenious torsional fatigue testing machines have been devised in which small turned specimens are subjected to controlled alternating torsional stresses. With these machines fatigue limits are determined by similar procedure to that adopted in the case of other types of fatigue tests.

The principle on which practically all such machines operate is similar and consists in applying a reciprocating angular movement of fixed amount to one end of a specimen, the other end being under a controlled restraint, either by the use of springs or by the use of adjustable masses, thus enabling the torsional stresses to be set to any desired figure.

A simple and convenient form of spring controlled machine is shown by the photograph, Fig. 30, which illustrates the Olsen-Foster type of apparatus.

In this arrangement, the ends of the specimen are secured in chucks attached to crank arms whose shafts are mounted in co-axial bearings.

One crank arm is given an oscillatory motion by means of a motor-driven secondary crank, whilst the crank secured to the other end of the specimen is mounted between two adjustable compression springs.

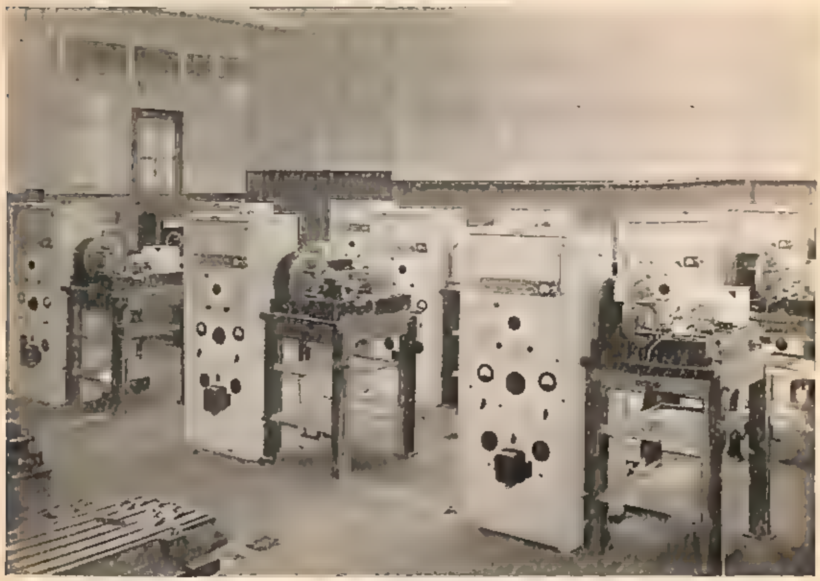


Fig. 29.

The oscillatory movement of this latter crank is a measure of the torsional oscillations transmitted by the specimen and is conveniently employed to give a record of the applied stresses.

HIGH TEMPERATURE TESTS.

The present-day trend towards the use of materials at higher temperatures has led not only to the development of materials capable of better resistance to these new conditions, but has brought about a new technique of design and testing to meet conditions under which the determining factor is not the elastic range of the material, but is rather the maximum stress under which the resulting continuous deformation of a structure will not impair its usefulness.

Apart from excessive oxidation, which occurs with some materials, the most important aspect of the behaviour of metals at high temperatures is the tendency to continuous deformation under load, a phenomenon now generally known as "creep."

Although it is now believed that fundamentally the mechanism of creep in metals at high temperature is not entirely the same as that occurring in such a material as pitch at normal temperatures, the visible characteristics are similar and both materials will continue to "flow" as long as the load is sustained.

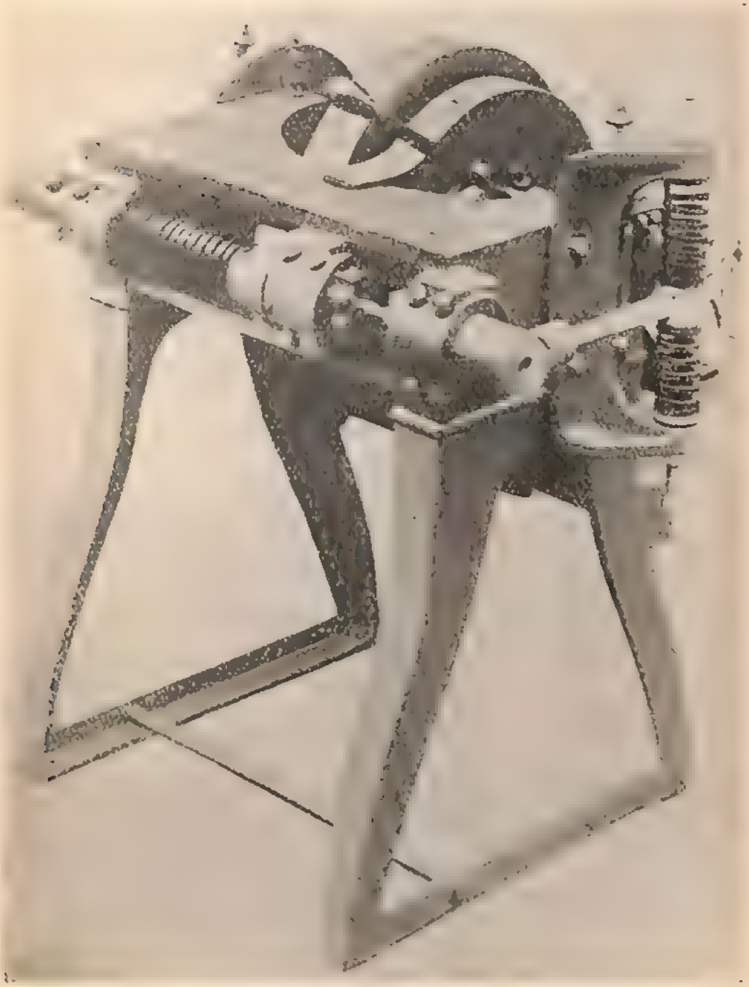


Fig. 30.

"Creep" in steels becomes of importance at temperatures of 350°C. or more, but for many non-ferrous metals susceptibility to "creep" is pronounced at much lower temperatures.

For design purposes it is necessary to know for any particular material the relation between the imposed stress and the working range of temperature, to produce various amounts of deformation in the assumed life of the machine.

This information can only be acquired by an extensive series of tests, in which the behaviour of a number of specimens of the material subjected to different stresses is measured over long periods of time at various temperatures.

Such procedure is necessary to obtain data suitable for design purposes, but if, as occasionally occurs, it is only required to obtain the relative behaviour of two materials, this can generally be satisfactorily carried out by a single "creep" test on each of the materials, or may even be obtained by comparatively simple tensile tests made at the working temperature and under a specially slow rate of straining.

The two methods of testing (*a*) "creep" testing and (*b*) slow-tensile testing, with the special equipment employed for these tests, are described in the following sections.

25. CREEP TESTING.

As the name implies, "creep" testing involves the measurement of the minute, but continuous deformation which occurs when materials are subjected to stress; generally but not always at high temperatures.

The test is practically always carried out on parallel, circular section, specimens under a simple tensile stress and appropriate methods of calculation are then used for design where other shapes and types of stressing are encountered. Creep under tensile or compressive stresses of the same magnitude is similar but of opposite sign.

A typical complete creep-strain diagram up to fracture at a temperature of t°C. and an initial stress of f tons/sq. in., including the permanent strain during loading (which may be zero) is shown by Fig. 31.

In this diagram creep-strain, *i.e.* permanent extension per unit length, is measured by the vertical ordinate and time by the abscissa.

It will be seen that the initial rate of creep is relatively very rapid, but that this rate diminishes with the progress of the test and later becomes for a time almost constant. After this constant rate period, the rate of creep steadily increases up to the point of fracture.

There are therefore three, and sometimes four, recognised phases in the creep of a specimen starting from the instant when

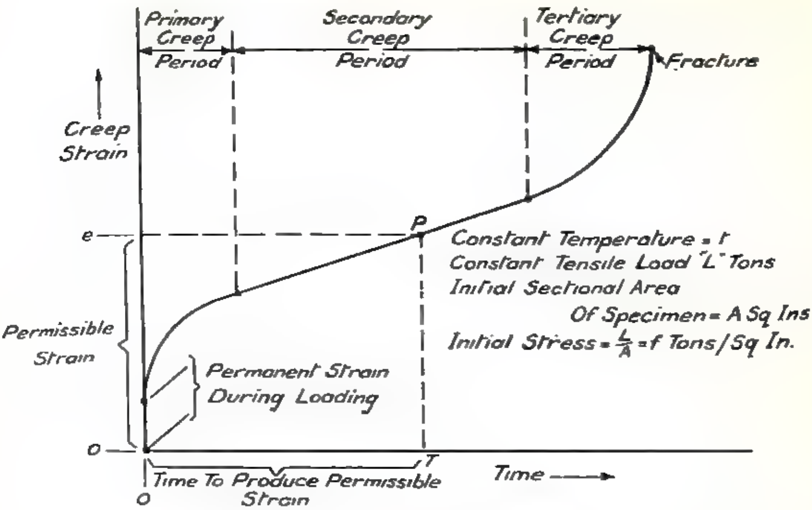


Fig. 31—Typical creep diagram.

permanent distortion commences (sometimes before the full load is applied) until the final fracture.

These four phases are set out below and can be related to those shown on the diagram, Fig. 31.

PHASE 1—"Initial Permanent Strain," which may or may not occur, depending on the magnitude of the load.

PHASE 2—"Primary Creep" period, during which the rate of creep diminishes to a constant value.

PHASE 3—"Secondary Creep" period, when creep proceeds at an approximately constant rate.

PHASE 4—"Tertiary Creep" period, in which the rate of creep increases up to the point of fracture.

The summation of the creep during these four phases on which design is based, is the total creep strain to fracture and is dependent on (*a*) the material, (*b*) the operating temperature and (*c*) the stress.

Long time creep tests made in order to obtain design data are generally, but not always, carried into the secondary period ; they are rarely extended until the specimen fractures.

Short period creep tests up to fracture, known as "Stress to Rupture" tests are now commonly employed for rapid checks of the creep performance on batches of material or parts.

A wide variety of different creep machines and specimens, most of which are generally satisfactory, are employed for testing by different investigators and it is difficult to put special emphasis on any one type of machine or specimen, although as far as the

specimen is concerned, it may be noted here that specimens of 0·357″ dia. (0·1 sq. in.) and of 5″ gauge length with spherically seated dumbbell ends would represent good normal practice.

(*a*) **Tests for Design Data.**

In order to investigate, for design data, the creep properties of any particular material, a number of test specimens would be turned from a sample of the material to a shape suitable for the creep testing machines available.

Specimens are normally provided with attachments for an extensometer and are suspended complete with the extensometer and thermocouples inside a thermostatically-controlled furnace by means of which the specimen gauge length is maintained at a uniform and constant temperature.

When the temperature has been stabilised at the desired value, tensile load is then applied to the specimen without shock up to the amount necessary to produce the required stress.

Should the stress × strain relation for the material be required at the test temperature, the creep test load would not be put on all at once but would be applied in a number of suitable increments, noting the corresponding extensometer readings. This procedure has the additional advantage in that it gives a reliable measure of the permanent deformation during loading, otherwise difficult to determine.

Immediately the full test load is reached, extensometer readings of the creep are commenced and are continued at suitable intervals until the predetermined permissible strain in the specimen, point P in Fig. 31, is obtained. Test periods for this type of investigation usually fall between 200 and 4000 hours for different specimens.

Data for design purposes is most usefully presented in the form of a curve or curves giving the relationship between the safe working stress and the operating temperature for a permissible amount of strain in the estimated useful life of the plant or apparatus. Such a curve is shown in Fig. 32. It should be noted that the assumed "life-time" of the plant becomes an important factor in the design.

As it may not be clear how the design data chart, Fig. 32, is obtained, the following brief summary of the procedure is appended. It will be observed that for one material sixteen separate tests are necessary to produce the data chart.

In view of the great variety of engineering materials and their applications all having their appropriate range of operating temperature, the discussion following is necessarily dealt with in general terms as temperatures, stresses, permissible strains and life periods, would be determined by the intended service. These factors are, therefore, referred to as t (temperature), f (stress) and e (permissible creep strain in life-time T_x).

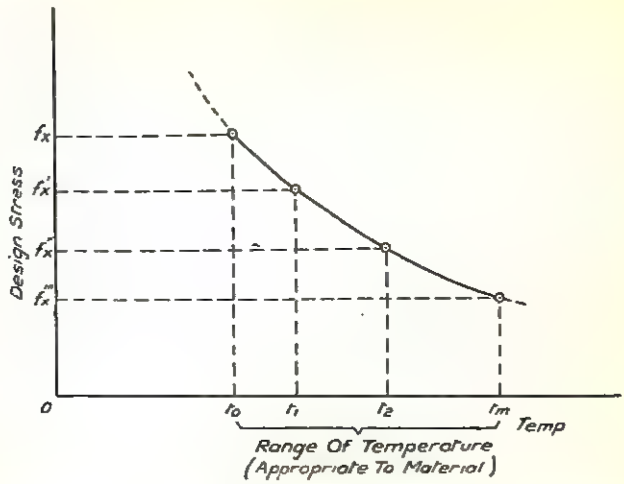


Fig. 32—Chart of design stress against temperature on basis of permissible creep strain "e" in lifetime Tx.

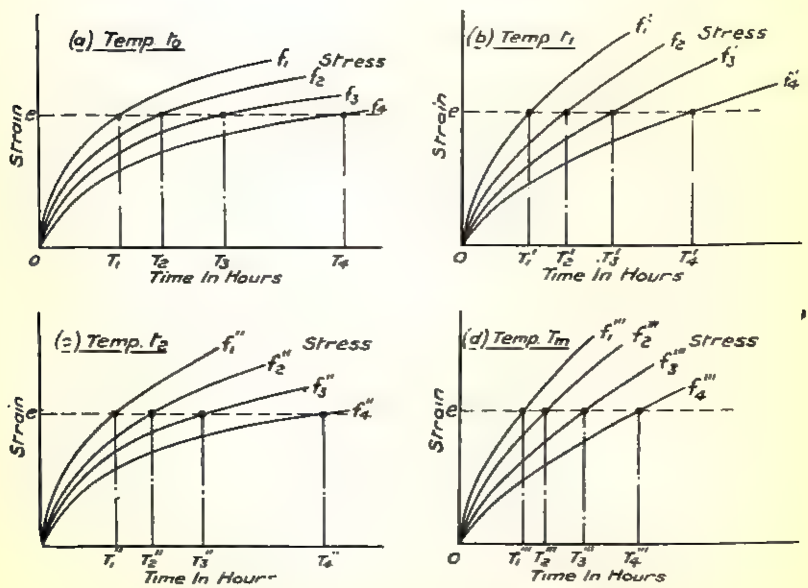


Fig. 33—Graphs of creep strain against time.

For any particular material, the probable useful range of working temperature t_0 to t_m degrees, will generally be known.

(i) Within the appropriate range of temperature for the material, four reasonably-spaced temperatures t_0, t_1, t_2 and t_m are selected.

(ii) For each of the above four temperatures, creep tests are made at four different stresses (f_1, f_2, f_3, f_4), (f_1', f_2', f_3', f_4'), etc., which are continued until the permissible strain "e" is reached. The results of these tests are plotted in the form shown by Figs. 33 (a) to (d).

(iii) From each of the Figs. 33 (a) to (d), four relations between the stress (f) and the time (T) to reach the permissible strain "e" are obtained.

Corresponding values of f and log T are then plotted to give the four curves, Figs. 34 (a) to (d), and are extrapolated to obtain the stresses f_x, f_x', f_x'' and f_x''', which at the particular temperatures t_0, t_1, t_2 and t_m will produce the permissible strain "e" in the selected "life" period T_x (100,000 hours for most industrial cases).

(iv) The four values for "f_x" thus obtained are then plotted against the corresponding temperatures t_0, t_1, t_2 and t_m to give the design data chart, Fig. 32.

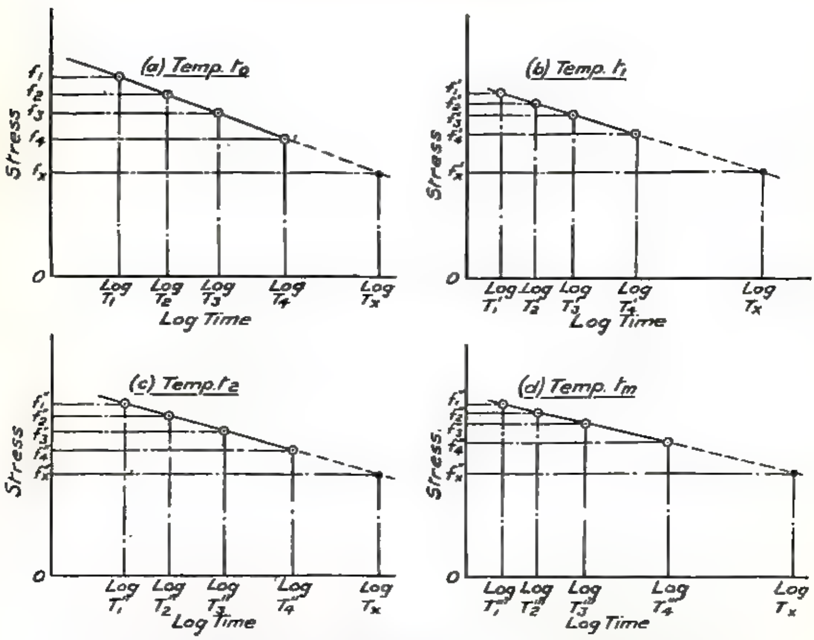


Fig. 34—Graphs of stress against log (time for permitted strain e) extrapolated to lifetime of machine (Tx).

(*b*) Acceptance Tests.

When testing batches of material for approval to some established standards of stress and temperature, a much shorter test period is convenient. The extensometer is usually dispensed with and only the time in hours between the full application of the load and fracture of the specimen is recorded as the criterion of performance.

The standardised period for such tests known as "Stress to Rupture" tests generally lies between 24 and 72 hours, so that the checking of a batch of material for creep properties can therefore be made in a reasonably short time.

A test of the character described, however, is only satisfactory when applied to the comparison of batches of the same type of material. It should not be used to compare the creep performance of essentially different materials which can only be done adequately by long time tests.

Creep Testing Machines.

The main essentials for the usual constant load, high sensitivity creep testing machine as used for obtaining design data are as given below—

(*a*) Means for applying constant tensile load to the specimen without shock and free from bending to an accuracy of $\pm$ 0·5%.

(*b*) Extensometer equipment for measuring the strain (extension per inch) of the specimen to an accuracy of $\pm$ 0·00001.

(*c*) Furnace equipment, with thermostatic control, capable of heating and maintaining the specimen to within $\pm$ 2°C. of the required temperature, with no greater difference than 2°C. along the gauge length at any period during the test.

(*d*) Thermocouples and temperature indicators capable of accurately measuring the temperature of the specimen to $\pm$ 0·3°C.

To achieve these requirements, apparatus of the very highest accuracy must be employed and maintained in perfect condition.

For less refined work such as the "Stress to Rupture," tests used for checking batches of material some relaxation in the requirements is possible, but owing to the important influence of temperature and stress on creep the tolerances on the accuracy of the heating and loading arrangements should not be greater than twice those given above for the high sensitivity equipment. As the "Time to Fracture" is the important quantity to be measured, it is generally not necessary to provide extensometer equipment.

(*a*) **High Sensitivity Creep Apparatus.**

The schematic arrangement of a high sensitivity type of apparatus, as used by the author, is shown by the diagram Fig. 35, in which the specimen with its extensometer is enclosed in a thermostatically-controlled furnace and loaded by means of an accurate 10 to 1 lever system, with knife-edge fulcrums.

The weights hung from the end of the lever, added to the effective weight of the lever itself, are adjusted to give the desired load on the specimen which at the start is all carried by the spring balance. When commencing a test the load can then be gently transferred at any desired rate from the spring balance to the lever by means of the hand-wheel shown. Readings of the extensometer are taken at suitable intervals during this process.

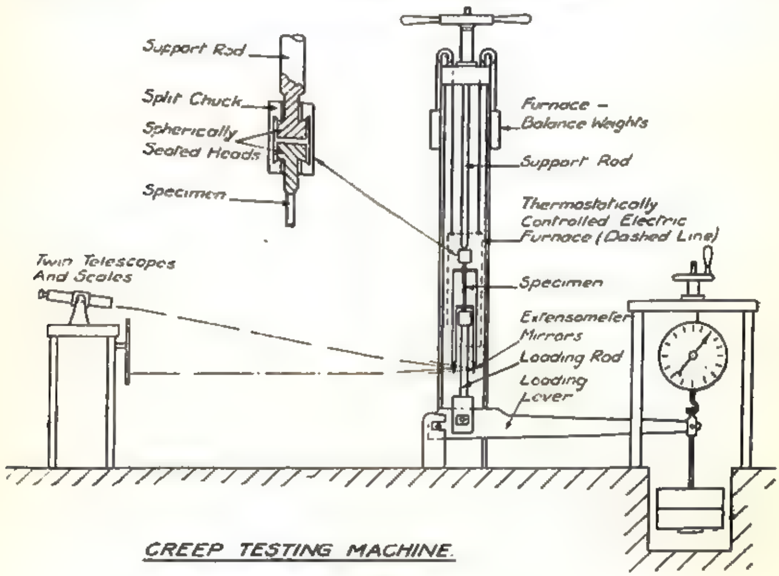


Fig. 35.

Photographs of two 6-unit installations, early and recent, as used for temperatures up to 700 and 900°C. respectively are shown by Figs. 36 and 37, the furnaces in the latter view being hidden by the side stanchions. Fig. 38 gives a view of one of the thermostatically-controlled 900°C. furnaces and specimen complete with loading rods, spherically seated shackles and extensometer standing to one side.

A more detailed view of the creep specimen, with extensometer attachments and the author's spherically seated shackles is shown in the photograph, Fig. 39.

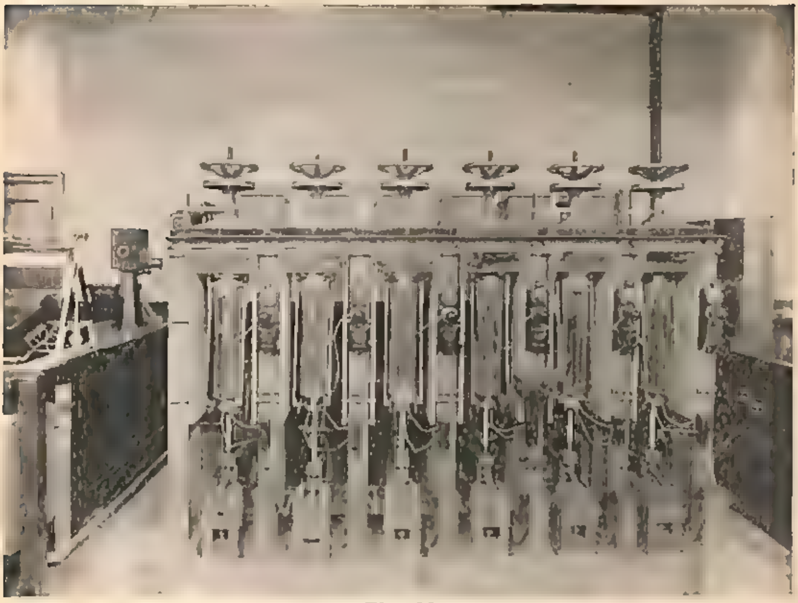


Fig. 36.

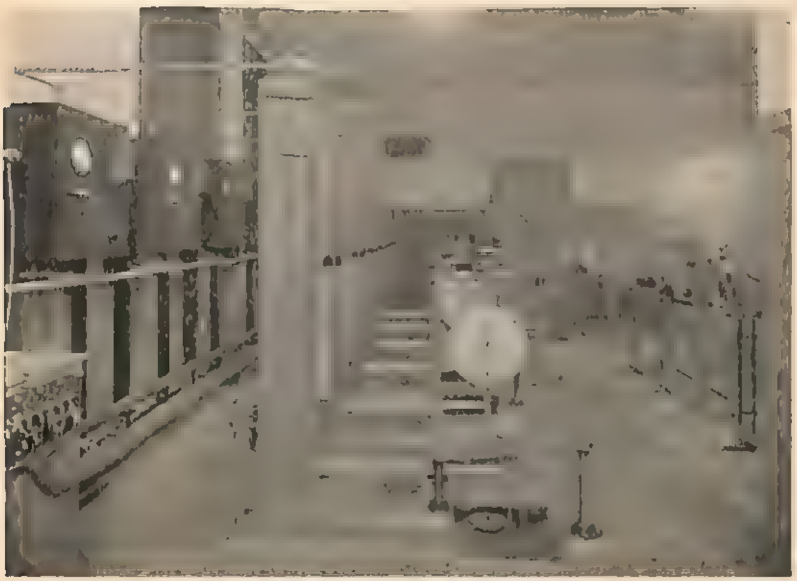


Fig. 37.

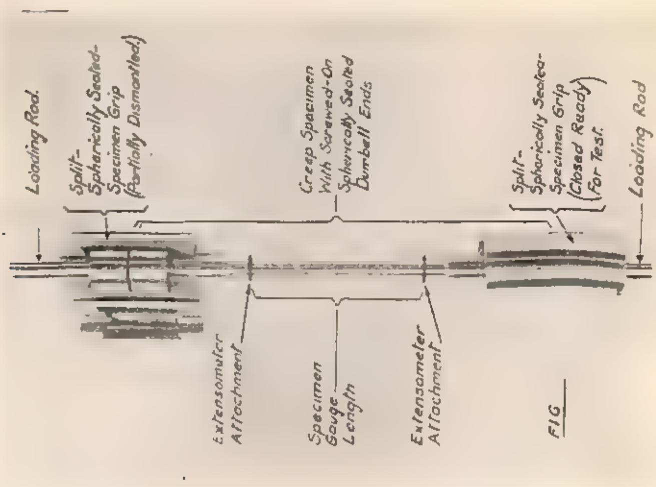

Loading Rod.
Split-
Spherically Seated-
Specimen Grip
(Partially Dismantled)
Creep Specimen
With Screwed-On
Spherically Seated
Dumbell Ends
Split-
Spherically Seated-
Specimen Grip
(Closed Ready
For Test.
Loading Rod
Extensometer
Attachment
Specimen
Gauge
Length
Extensometer
Attachment
FIG

Fig. 39.

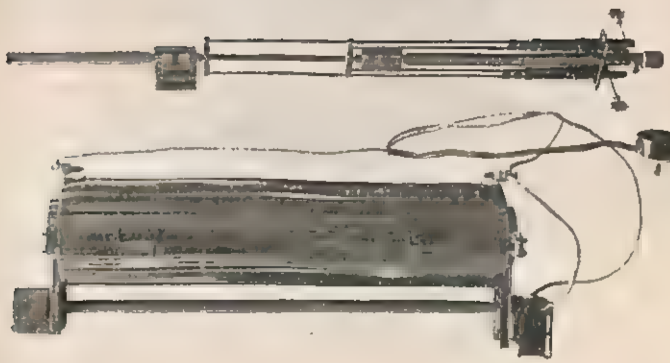


Fig. 38.

In practice, it is usual to have three thermocouples attached to the specimen, one near to either end of the gauge length and the third at the centre of the gauge length.

The thermocouples are connected to a pattress on the side of one of the stanchions and from there are permanently wired to the cold junction container and to a multi-channel switch by means of which any couple in the installation can be connected either to a millivoltmeter type of instrument for rough checking or to a potentiometer bridge and galvanometer for accurate measurement of the temperature.

In order to economise in floor space, Fig. 37 shows the extensometer telescopes and scales arranged on the same side as the loading levers.

(*b*) "Stress to Rupture" Apparatus.

As the "Stress to Rupture" tests are designed to check batches of material or machine parts which are often of small size, the test specimens are also necessarily small. No fixed standard appears to have been set, but one size used by the author, *i.e.* overall length 3″·25, parallel length 2″·5 and 0″·15 dia. is probably typical.

Owing to the small size of the specimens, it is therefore possible to reduce the size of the testing equipment proportionally. A complete six-unit installation used by the author is shown in the photograph, Fig. 40, the size of which can be judged by the chair.

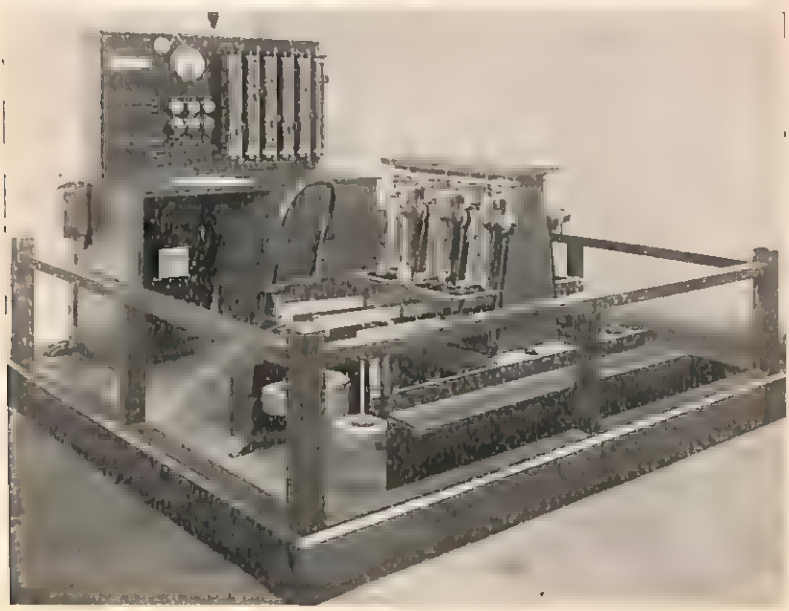


Fig. 40.

Extensometers are not attached to the specimens, although a rough measure of the extension can, if necessary, be obtained by means of the dial gauge shown in the illustration which indicates the fall of the loading lever.

As in the case of the high sensitivity equipment, thermostatically controlled furnaces are used and thermocouples attached to the specimens are connected to a pyrometer to indicate the temperature.

The usual test procedure is to measure the time taken to break the specimen under standard conditions of temperature and stress. In order to record the time to fracture, which may possibly occur during the night or at week-end, each of the six units is equipped with a break-switch which operates when a specimen fractures and as well as recording the time on a drum type of clock, also cuts off the heating current to the furnace.

Design based on Creep Data.

Design of machine components which in service are subjected to stress and high temperature for prolonged periods, cannot be dealt with by the usual methods which have proved satisfactory for structures and machines operating at normal or moderate temperatures.

The reason for this is that, provided the temperature is sufficiently high, important creep can occur at stresses which fall below the proportional limit for the material when measured in the usual way at the operating temperature. Therefore, as the proportional limit stress generally sets the upper limit for design, based on elastic theory, it will be evident that at high temperatures where creep occurs a continuous and cumulative distortion may result at stresses which appear to be otherwise quite satisfactory.

When designing a part on the basis of creep, the first important factors to consider are (*a*) the total period, T_x, during which the part will be exposed to the temperature and stress in the estimated "life" of the machine, and (*b*) the amount of strain, e, which can be permitted during the "life" of the machine.

Both T_x and e will vary with the particular service for which the part is intended. For many industrial applications, T_x may be taken as 100,000 hours (11·4 years) and e as 0·1% (i.e. equal to an extension of 1/10″ in a length of 100″).

It will be evident that special duties may require very different quantities, for example, as an extreme case, in jet propelled rocket parts $T_x = 1$ hour, would appear to be quite adequate.

Industrial projects, however, such as steam turbines, high temperature reaction chambers, boilers, super-heaters, etc., probably form the majority of applications where creep has importance with temperatures ranging between 200 and 550°C. Gas turbine

temperatures may be somewhat higher, possibly in the region of 650°C. for industrial applications.

A quantity of creep design data exists in published form for the ferrous materials used in industry, and the curves (a) to (f) of Fig. 41, give some fairly well-established relations between the design stress in tons/sq. in. and the temperature in °C. with a creep strain of 0·1% in 100,000 hours for a number of typical constructional materials.

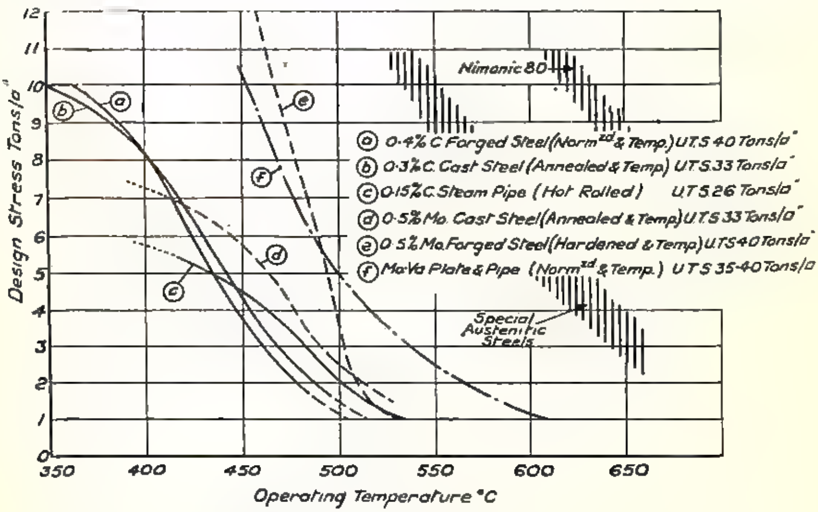


Fig. 41—Creep design data on basis of 0.1% strain in 100,000 hours.

The selection of a ferrous or high duty material for a particular service will, of course, depend on a number of circumstances apart from creep requirements. Neglecting all other considerations but creep properties and cost, the following table gives an indication of the range of temperature for which the various materials appear to be particularly suitable but which may have to be departed from where other considerations predominate.

Range of Temperature.	*Material (Ferrous).*
Below 250°C. ...	Creep has little significance and design can be based on elastic theory.
350 to 420°C. ...	Carbon steel, forged or cast.
420 to 480°C. ...	0·5% Mo. steel, forged or cast.
480 to 535°C. ...	Mo-Va steel.

At temperatures above 550°C. where appreciable stress occurs, special austenitic steels or non-ferrous metals, such as Nimonic 80 would generally have to be employed.

Long period creep data on these materials is practically non-existent at the present time, but extended extrapolations from short period tests suggest that some of the better austenitic steels and Nimonic 80 would fall within the shaded regions indicated on the diagram, Fig. 41.

Much information on the short period creep properties of these very special high duty materials and some light alloys, with particular reference to gas turbines for aircraft, can be obtained from the following publications :—

(i) Symposium on Materials for Gas Turbines—A.S.T.M., June, 1946.

(ii) Heat Resistant Alloys from 1200° to 1800°F.—"Iron Age," March and April, 1948.

26. TENSILE DATA AT HIGH TEMPERATURES.

In a paper to the Institution of Mechanical Engineers, by Mr. R. W. Bailey and the present author, read in February, 1932, it was shown that the rate of straining produced a marked effect on the tensile strength of a metal when tested at high temperatures.

For the case of a 30-ton 5% nickel steel, results were given which showed that although the rate of straining had little effect over the range investigated up to a temperature of 150-200°C. the difference in results became very important between 250-300°C.

These results indicate the importance of specifying the straining rate for all high temperature tensile tests and point to the need for standardisation of this rate ; the above paper recommends a rate of one-thousandth of the gauge length per minute.

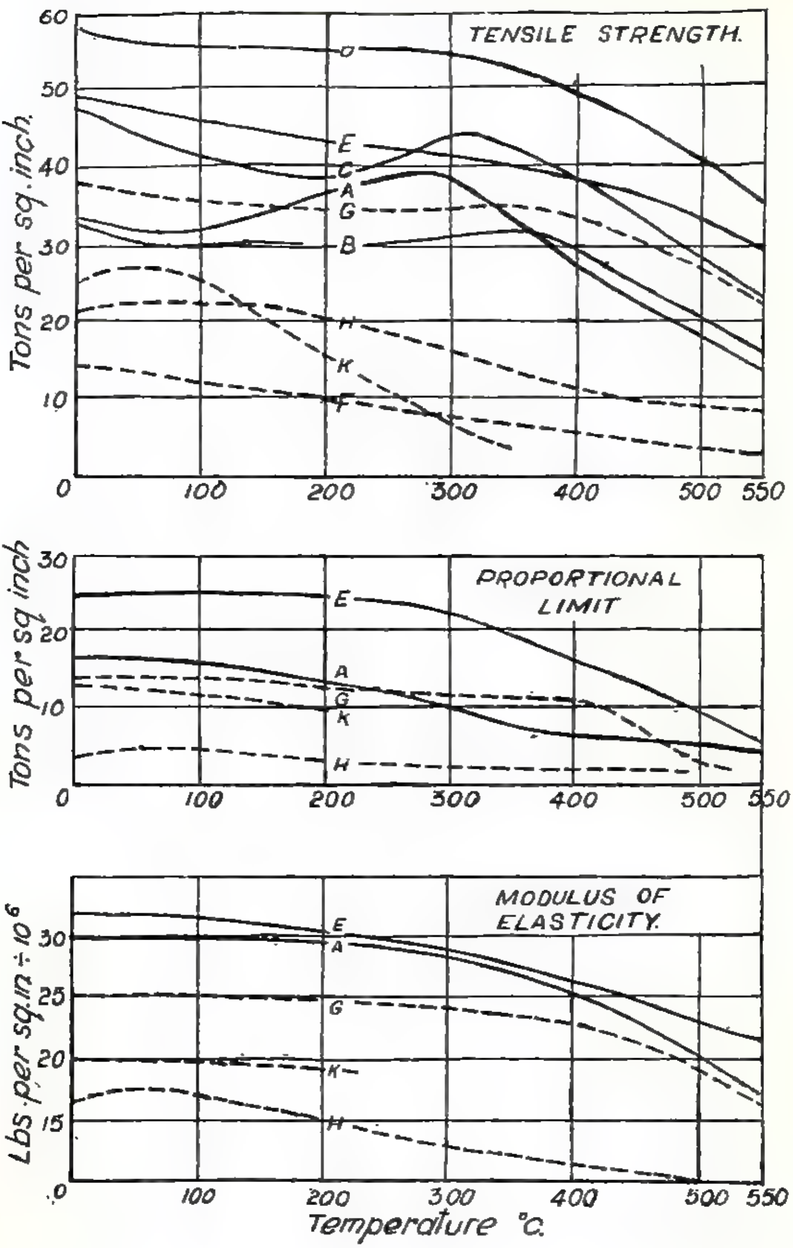
Where comparison with "creep" data is desired the testing temperature for steels should be 550°C., as this temperature ensures that thermal hardening effects observed at lower temperatures will be negligible.

The large majority of the tensile testing of metals at elevated temperatures has, however, been carried out at the normal straining rates employed in ordinary commercial testing, and whilst such data has only a restricted value, it does serve to indicate in a general way the capacity of a material for high temperature service.

For this reason a selection of curves showing the relation between temperature and important physical properties is given for various structural materials by Fig. 42.

Particulars of these materials are given below :—

A—Mild steel, normalised—0·37% C.
B—30-ton nickel steel. OH and T—0·068% C., 4·8% Ni.
C— ,, ,, ,, ,, —0·22% C., 5·1% Ni.
D—Ni - Cr - Mo Steel—0·3%, 0·6% Cr., 2·4% Ni, 0·8% Mo.



TENSILE STRENGTH.
Tons per sq. inch.
60
50
40
30
20
10
0
100
200
300
400
500
550
D
E
C
A
G
B
H
K
F
PROPORTIONAL LIMIT
Tons per sq inch
E
A
G
K
H
MODULUS OF ELASTICITY.
Lbs. per sq. in ÷ 10^6
E
A
G
K
H
Temperature °C.

Fig. 42.

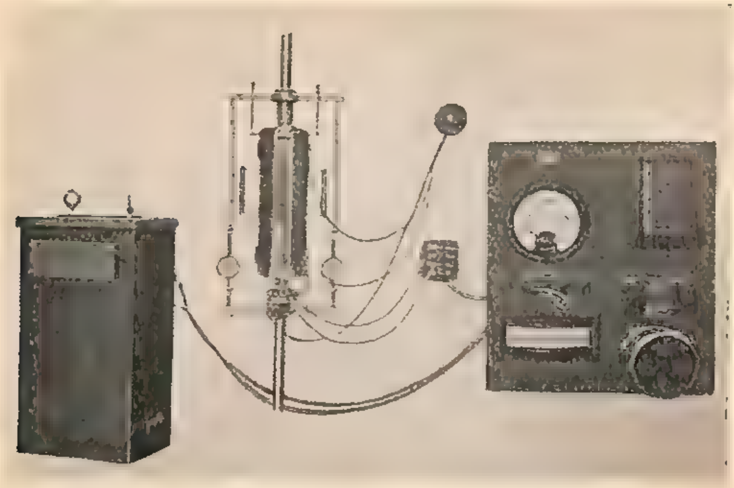


Fig. 43.

E—Stainless steel—0·25% C., 13·5% Cr.
F—Copper, annealed—commercially pure.
G—Monel metal.
H—Phosphor bronze.
K—Duralumin.

Apparatus used by the author for carrying out either slow or normal rate tensile tests at high temperature and used in conjunction with any normal type of tensile testing machine, is shown by the photograph, Fig. 43.

TESTS ON WELDS.

The testing of welds has of recent years acquired a considerable importance and attracted much attention, mainly due to the extension of welding into such industries as shipbuilding, bridge and structural engineering and to the manufacture of steel pressure vessels.

It is in these and similar industries that weld testing and approval is controlled by the inspecting engineers of such organisations as Lloyds Survey, The British Corporation and the various insurance companies.

These bodies, together with the British Standards Institution, have now set a standard for welds, which makes it imperative for the manufacturers both of the fabricated equipment and of the welding appliances to maintain an equally high standard in their products and has indirectly led to an all-round improvement in the welding art.

The testing of welds may be roughly divided into two sections—(1) destructive testing, in which weld specimens are tested by the usual methods of tension, bending and impact, etc., and (2) non-destructive testing, by means of X-rays, gamma rays, and magnetic or electrical methods.

Except to note that although X-ray inspection is, in the absence of better methods, now specified in certain special cases by some authorities, it is not proposed to deal with non-destructive tests, as these are at present all in the experimental stage and not sufficiently positive or discriminating for general industrial use.

The destructive type of test is still, with all its limitations, the only satisfactory method of testing welds and with proper precautions it can be used to obtain a valuable indication of the quality of the welds in a structure.

Tests of this character which have been devised and are now in common use are, with suitable modifications, based on the well-known tensile, bend and impact tests such as are used for the testing of steel forgings.

In view of the limited nature of the material available, which is generally in the form of a narrow band connecting two plates or rolled sections, it is necessary to adopt special procedure in order to dissociate the behaviour of the weld metal from that of the parts which it connects together.

In practice, it is also generally found necessary to prepare special test samples, as it is almost always impracticable to cut specimens from the finished structure.

This procedure makes it essential to provide adequate inspection of the actual manufacture to ensure that the standard of welding employed in the preparation of the test samples is maintained in the structure.

Destructive tests may be divided into two groups—(1) Joint Tests and (2) All Weld-Metal Tests. The former method has undoubtedly the greater practical value, as it is possible to reproduce with this type of test the exact conditions under which the structural joints are made and the test may be made to give an indication of the characteristics of the junction between the weld deposit and the structural member as well as of the deposit itself.

All weld-metal tests are now practically confined to acceptance tests for welding rods, for which purpose they have considerable value, although in certain cases where the character of the deposit and the parent metal is different the test should be treated with caution, as the limiting factor in such cases is frequently found in the junction between the two materials.

27. TESTING PROCEDURE.

Although most of the test specifications which have been devised have particular reference to the metallic arc process, they are almost

equally well suited for other welding processes, including (1) oxy-acetylene, (2) carbon arc and (3) atomic hydrogen.

Many of the tests are based on American practice, in which country the application of welding to important structures was generally in advance of that of other countries.

The testing procedure and specifications set out in the following sections are representative of average present-day practice and are based on the requirements of a number of authorities. They do not necessarily conform to the rules of any one particular institution.

It will be found, however, that they are in general agreement with the B.S.I. Specification 538, 1934, to which reference may be made for more detailed procedure.

28. PREPARATION OF TEST SPECIMENS.

In all cases test specimens should be prepared by the operators engaged on the welding of the structures concerned.

The conditions of welding and the plant employed should also be the same as is used during the actual manufacturing process.

In cases where welding rods are employed, these should be taken from the stock set aside for use on the structure and deposition should be carried out under the conditions of current, etc., as specified by the manufacturers of the rods

29. JOINT TESTS.

The plate material used for test purposes should in all cases be taken from the stock set aside for use on the structure.

A. Tensile and Bend Tests.

Tensile and bend test specimens are prepared by welding together the chamfered edges of two pieces of plate, each being conveniently about 6″ or 8″ square.

The welded seam is then ground flush with the surface of the plates, which, without further treatment, are afterwards sawn into strips of convenient size for testing, as shown by the diagram, Fig. 37A. The average test requirements of the various specifications are :—

Tensile test,	26/28 tons-sq. in. min.
Bend test,	90° without sign of failure over a former of radius equal to twice the plate thickness.

B. Fillet Tests.

The resistance of welded joints to failure under static loading in practically all cases can be related to the strength of the joint under tensile or shear stressing.

For this reason it is usual to carry out two types of test on fillet joints such that the final failure is governed either by the tensile or shear strength of the weld deposit.

The types of specimen employed for these tests are shown respectfully by (B) and (C), Fig. 44, and the average test requirements are as given below :—

Tensile strength calculated on minimum section,	26/27 tons/sq. in. min.
Shear strength calculated on minimum section,	16/18 tons/sq. in. min.

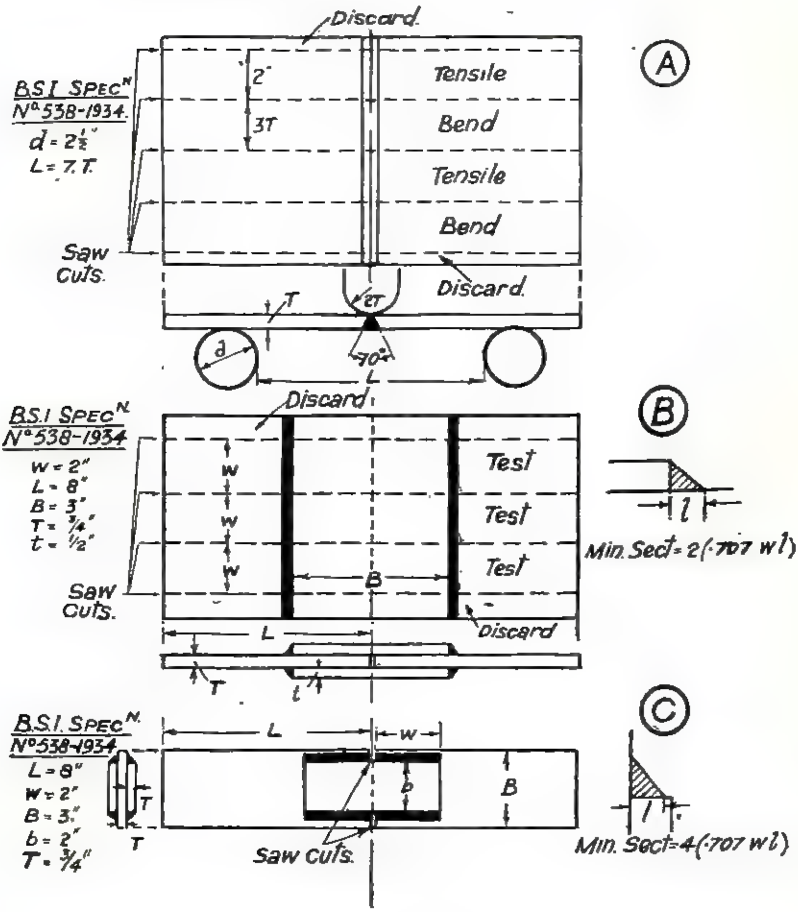


Fig. 44.

Occasionally tests are required in which one plate T'eed on to another by means of two fillet runs is required to bend through 90° without failure of the welded seams.

Such tests, however, do not appear to add any useful information to those already described.

30. ALL WELD METAL TESTS.

Specimens whose test length is machined entirely from deposited metals are now generally prepared either by depositing successive layers of weld metal on to a rigid mild steel bar until sufficient section is built up for test purposes, or by filling up the gap between two chamfered plates resting against a suitable backing plate. The surplus bar or backing plate is afterwards machined completely away.

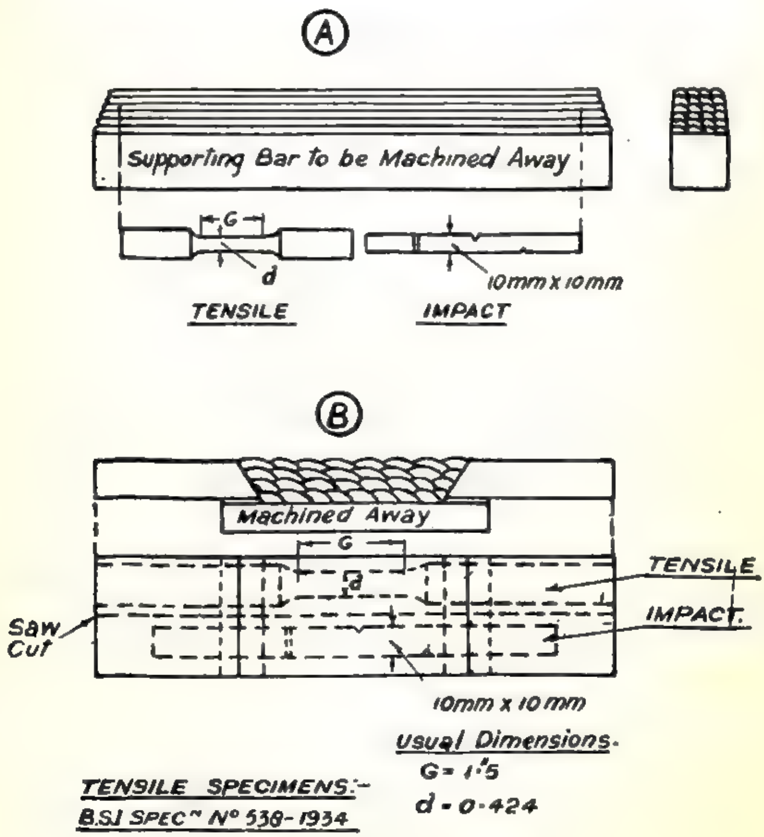


Fig. 45.

The two methods described are illustrated by the diagrams Figs. 45 (A) and (B). Of the two, the latter procedure has much to recommend it on the ground of its economy in time and welding rods.

As in the case of the joint tests the deposition of metal should be carried out by the operators employed on the structure, using the same plant and welding conditions as specified by the manufacturers of the welding rods.

The average of the minimum requirements now in operation for first grade welding rods are :—

TENSILE.

U.T.S. tons/sq. in.	El.% on $4\sqrt{A}$
26/28 min.	18/20 min.

IMPACT TEST.

10 mm. × 10 mm. Izod specimen—30 ft./lbs. min.

31. OTHER METHODS OF DESTRUCTIVE TESTING.

When carrying out tests with parallel-sided specimens by the methods described above, it frequently occurs that the tensile specimen fractures not at the weld but in the adjacent parent plate material. Also in the bend test the ability of the weld joint to bend satisfactorily is often obscured by the bending of the plate immediately adjoining the weld.

For many purposes the knowledge that the weld is stronger than the plate is sufficient, but for those cases where particulars of the actual strength of the weld is desirable, together with information as to the true bending properties of the weld, the form specimen shown by the diagram and table, Fig. 46, can be usually employed.

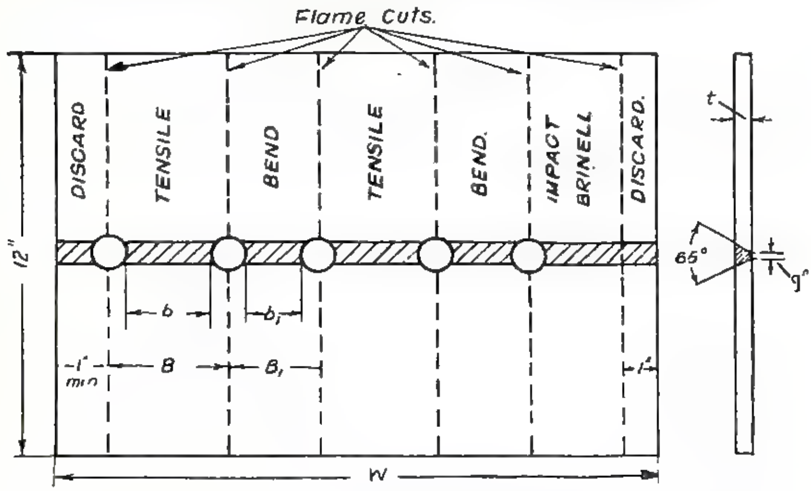
More complete data regarding this form of test may be obtained by reference to *Engineering*, Feb. 2, 1934.

THE TESTING OF CEMENT.

Although there are actually a number of different types of cements in existence, the use of the familiar hydraulic Portland cement has now become so universal that the present description of testing methods has been written with reference to this cement alone.

Portland cement is manufactured from a watered mixture of chalk or limestone (CaO) and clay (SiO_2 + Al_20_3) which are ground together, the resulting sludge afterwards being dried and then burned or calcined in a special kiln. Finally the burnt product is ground to the very fine powder known as Portland cement.

As this material can vary very widely in properties if not carefully blended and manufactured, a fairly elaborate testing technique has been developed, with the object of ensuring a uniformly good quality material.



t''	B″	b''	B_1''	b_1''	d''	g''	W″	$A=bt$
$\frac{1}{4}$	$1\frac{1}{4}$	$\frac{3}{4}$	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{16}$	12	0·1875
$\frac{3}{8}$	$1\frac{7}{8}$	$1\frac{1}{8}$	$1\frac{1}{2}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{32}$	12	0·422
$\frac{1}{2}$	$2\frac{1}{2}$	$1\frac{1}{2}$	2	1	1	$\frac{3}{32}$	13	0·75
$\frac{5}{8}$	$3\frac{1}{4}$	2	$2\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$\frac{3}{32}$	16	1·25
$\frac{3}{4}$	3	$1\frac{3}{4}$	$2\frac{3}{4}$	$1\frac{1}{2}$	$1\frac{3}{4}$	$\frac{3}{32}$	16	1·312
$\frac{7}{8}$	$2\frac{5}{8}$	$1\frac{3}{8}$	$2\frac{5}{8}$	$1\frac{3}{8}$	$1\frac{1}{4}$	$\frac{1}{8}$	14	1·203
1	$2\frac{1}{2}$	$1\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$\frac{1}{8}$	14	1·25

Fig. 46.

The usual tests as specified by most authorities with little variation include (A) Fineness, (B) Chemical composition, (C) Tensile strength of neat cement, (D) Tensile strength of a mixture of cements and sand, (E) Setting time and (F) Soundness.

These tests, which are fully described in the British Standards Institution Specification No. 12, are briefly given in the following sections. All tests refer to material which has previously been aerated for 24 hours at 58-64°F.

32. SPECIFICATION TESTS.

A.—Fineness Test.

Four ounces of the neat cement when shaken for 15 minutes in a standard 180 × 180 sieve shall not leave more than 10% residue.

A similar quantity shaken for five minutes in a standard 76×76 sieve shall not leave more than 1% residue.

The standard sieves have a sieving area of 50 sq. inches and a depth of $2\frac{3}{4}''$ (min.).

A 180×180 standard sieve is made from 0·0018″ wire, with limits of between 178/182 wires per inch.

A 76×76 standard sieve is made from 0·0044″ wire with limits of between 75/77 wires per inch.

B. Chemical Composition.

After deduction of the lime necessary to combine with the sulphuric anhydride (SO_3) present the ratio of lime (CaO) to Alumina (Al_2O_3) + Silica (SiO_2) shall be within the limits of 2·9 to 1 and 2·0 to 1. Also :—

The insoluble residue shall not exceed	1·5%
Magnesia shall not exceed	4·0%
The total sulphur (as SO_3) shall not exceed	2·75%
The total loss on ignition shall not exceed	3%

C. Tensile Tests (Neat).

Neat cement mixed with a suitable proportion of water is filled into moulds to produce the shape of test specimen shown by the diagram, Fig. 47A. The temperature of the room and of the water used during any stage of the test shall lie between 58-64°F.

The mixing of the cement and the filling of it into the moulds must be carried out using a gauging trowel weighing $7\frac{1}{2}$ ozs. ; the moulds may be shaken down but must not be rammed.

After remaining in the moulds for 24 hours in a damp atmosphere, the specimens are to be submerged in clean water and left until required for test.

The tests can be conveniently made by means of the equipment shown by Fig. 24 and using special loading shackles of the shape shown by the diagram, Fig. 47B.

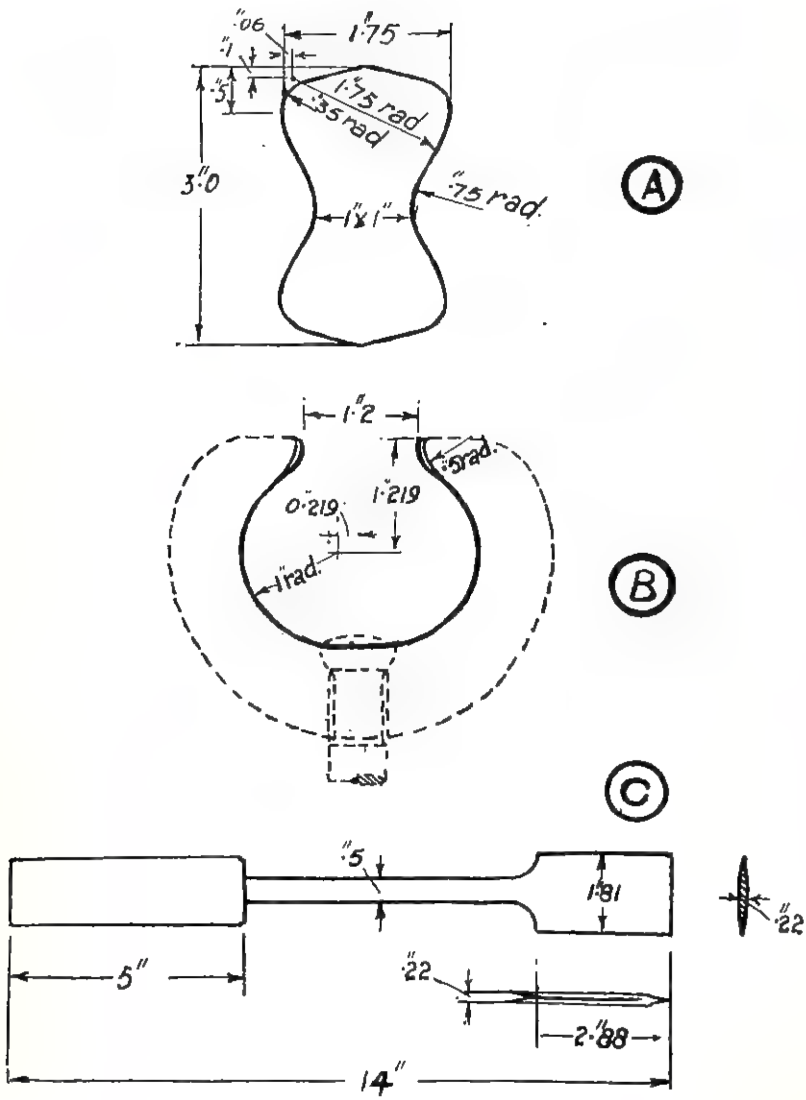
Six specimens shall be tested after six days' immersion in water and shall give a tensile strength of not less than 600 lbs. per sq. inch.

D. Tensile Tests (with Sand).

The mixture by weight shall consist of one part of dry cement to three parts of standard sand.

This shall be mixed with a percentage weight of water determined by the formula, $\frac{1}{4}$ P + 2·5, where P is the percentage used in the preparation of the neat cement specimens.

Filling of the test moulds is carried out with the standard spatula shown by the sketch, Fig. 47C. After standing 24 hours in a damp atmosphere the specimens are then to be immersed in clean water until required for test.



A
B
C
·06″
·1″
·5″
1·75″
1·75″ rad
·35 rad
3·0″
·75″ rad.
1″×1″
1·2″
·5 rad.
0·219″
1·219″
1″ rad.
·5″
1·81″
·22″
5″
·22″
2·88″
14″

Fig. 47.

Specimens tested after 7 and 28 days shall give the following minimum strengths :—

After 7 days, 325 lbs./sq. in.
After 28 days, Strength at 7 days

$$= \frac{10{,}000}{\text{Strength at 7 days}} \text{ lbs./sq. in.}$$

The standard sand used in the preparation of these specimens shall be obtained from Leighton Buzzard and shall comply with the following requirements :—

Loss on extraction with hot hydrochloric acid not more than $\frac{1}{4}\%$.

The sand shall pass through a 20×20 sieve and be retained on a 30×30 sieve.

The 30×30 standard sieve shall have 30 wires per inch of diameter 0·0108″.

The 20×20 standard sieve shall have 20 wires per inch of diameter 0·0164.″

E. Setting Time Tests.

Material for these tests shall be prepared in the same manner and under the same conditions as for the tensile tests on neat cement.

The mixture shall then be filled into the round mould shown on the base of the apparatus in Fig. 48A and shall be given a smooth level surface before testing.

Initial Setting Time.—The initial setting time shall be determined by the period between the adding of the water and the time when the Vicat needle (a) just fails to penetrate completely into the cement when gently lowered. For normal cements this period should not be less than 30 minutes.

Final Setting Time.—The final setting time shall be determined by use of the Vicat needle (b) and setting of the cement shall be regarded as completed when only the centre needle makes an impression.

The final setting time should not be more than 10 hours.

Quick Setting Cements.—For quick setting cements, the following times are specified :—

Initial setting time not less than 5 minutes.
Final setting time not more than 30 minutes.

F. Soundness Tests.

Soundness tests are carried out by filling the mould of the Le Chatelier apparatus, Fig. 48B, with cement prepared in the same manner as for tensile tests on neat cement.

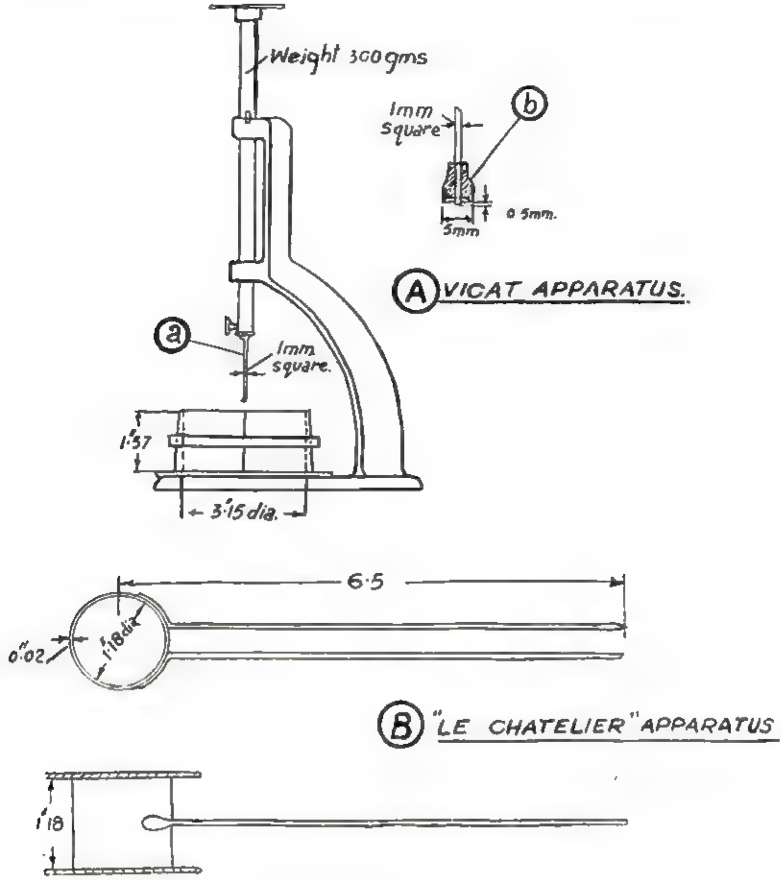


Fig. 48.

During filling the edges shall be held together and the whole immediately immersed in water with glass plates underneath and on top.

After 24 hours the distance between the indicating points shall be measured, the water is then brought to boiling point, and held for six hours, after which the mould shall be removed, cooled and the points remeasured.

The difference between the two measurements is the expansion of the cement and shall not exceed 0·40 inch.

If the sample fails to comply with the specification, a further sample shall be aerated for seven days before tests, when the final expansion determined as above shall not exceed 0·20 inch.

TEST PROCEDURE.

One of the most important branches of mechanical testing is that concerned with the testing for approval of forgings of all types, whether manufactured from carbon or alloy steels.

It is a fundamental rule of all such tests on forgings, no matter what the size or material, that they shall be put into their finally heat-treated condition before any tests are taken.

The correct selection of test material from the most convenient and representative positions on the forging is a matter which has developed from the experience of generations of engineers, but is now fairly well established for all common types of forging.

A few examples detailing the procedure employed for some of the more frequently used shapes of forging, which applies to both carbon or alloy steels, are given in the following sections, although the physical properties and test data given refer specifically to carbon steel forgings.

Alloy steel forgings being generally required for specialised services will naturally vary widely in their composition, depending on the particular conditions under which they are required to operate.

For this reason it is not possible to give any generalised specifications for their physical properties, although it should be borne in mind that, on account of the tendency to brittleness of some alloy steels under faulty heat treatment, it is always desirable to include an impact test in any specification for alloy steel where toughness in the finished product is important.

The impact test requirements for alloy steel forgings vary with different inspecting authorities. In some cases a minimum Izod impact value of 20 ft./lbs. is permitted, although with others a minimum of 35 ft./lbs. is required ; the latter figure, however, appears to be unnecessarily high, except for those cases where severe shocks may be expected in service.

33. SHAFTS (STRAIGHT).

Individual Cases.—Test material for straight shafts is invariably obtained by forging an extra 8″ or so on one or both ends, depending on the finished length of the shaft. As an approximate rule it may be taken that for shafts up to 8 ft. in length test material at one end only is sufficient, but for shafts longer than 8 ft. tests from both ends are necessary.

The main reasons for testing both ends of the longer shafts are because of the increased liability to variation in the composition from end to end and to the increased difficulty of applying a uniform heat treatment.

Batches.—When shafts are ordered in quantities, it is permissible in the case of the smaller forgings 6 ft. or less in length to test fully

only one shaft of the batch made from the same cast, the remainder of this cast up to a maximum of 50 being checked for uniformity by the Brinell hardness test.

In the case of intermediate sized shafts of from 6 to 10 ft. it is possible to reduce the amount of testing to say one in three from the same cast, the remainder being Brinell hardness tested for uniformity. Larger shafts than these should be treated individually.

Test Specimens.—The arrangement of the test specimen in relation to the shaft forging is shown by the sketch, Fig. 49A.

Dimensions of these specimens will vary to some extent, depending on the inspecting authority, but as a general rule for both carbon and alloy steel forgings the tensile specimens will conform to Table 1. Bend specimens will be either $1'' \times \frac{3}{4}''$ or $1'' \times 1''$ section in the case of carbon steel and $\frac{3}{4}'' \times \frac{3}{8}''$ for alloy steels.

Test Specifications.—The test requirements for forged carbon steel shafts generally permits a range of 4 to 5 tons in the tensile strength, with appropriate adjustments in the percentage elongation.

It will be found that most specifications for carbon steel shafts are included in the following general example :—

	Yield Point (min.) tons/sq. in.	U.T.S. tons/sq. in.	El. % (min.)
TENSILE.	50% U.T.S.	28 to 40	U.T.S. + %El. = 60
	U.T.S. tons/sq. in.	Radius of former.	Angle of Bend.
BEND.	28 - 32	$\frac{1}{4}''$	180°
	32 - 36	$\frac{3}{8}''$	180°
	36 - 40	$\frac{5}{8}''$	180°

34. SHAFTS (CRANKED).

Number of Tests.—Considerable difference exists between different specifications as to the position and number of tests which should be taken from crank shaft forgings.

The more stringent specifications require tests to be taken from either end of the shaft and also in three mutually perpendicular directions from the material lying between the webs of each crank throw.

Other specifications are less exacting and are content with tests taken in one direction from the material between each of the crank webs, or in certain cases of small-throw cranks, longitudinal tests only are taken from the shaft ends.

For most services a single test from the web material supplemented with a longitudinal bend test with Brinell hardness tests from the shaft end appears to be all that is necessary, particularly as it is usual to take tests from every forging in a batch of crank shafts.

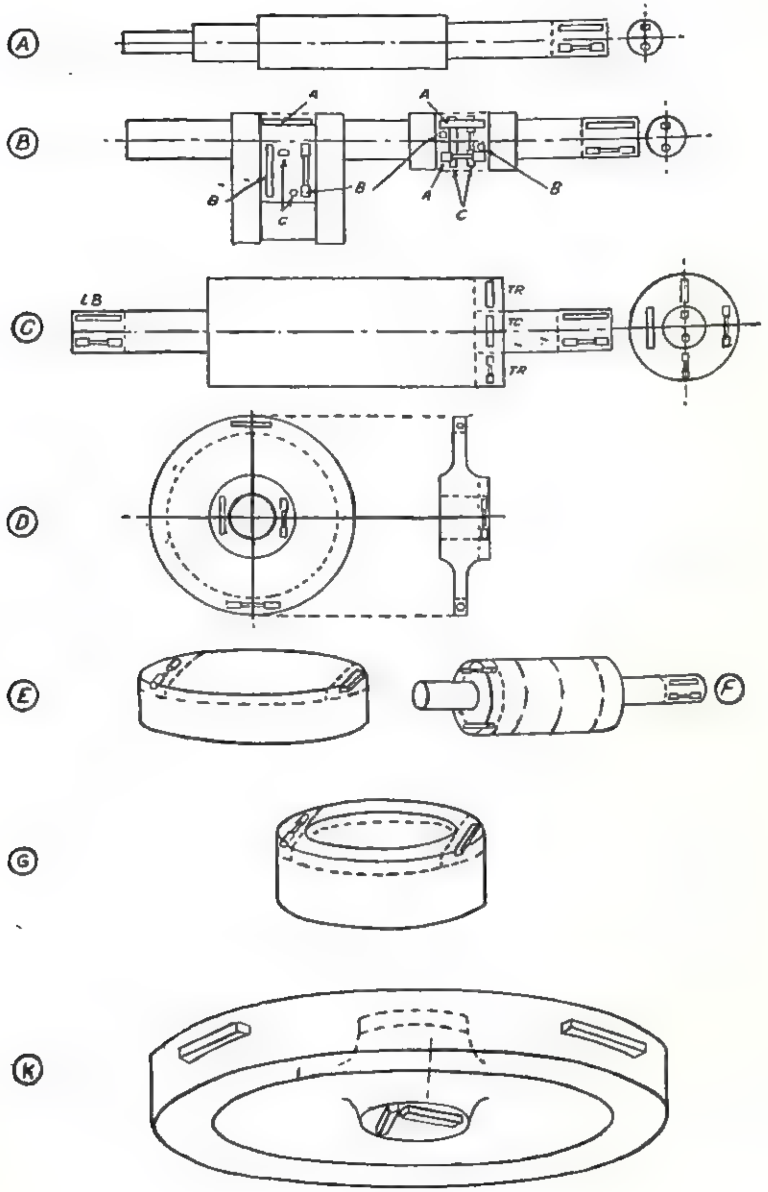


Fig. 49.

Test Specimens.—The locations of a complete set of test specimens in a two-throw crank are shown by the sketch, Fig. 49B, their dimensions being usually the same as those used in the case of straight shafts.

Test Specifications.—Average test requirements for these specimens on carbon steel forgings are as given below.

	Y.P. (min.) tons/sq. in.	U.T.S. tons/sq. in.	El. %	Angle of Bend (min.)
Shaft Ends,	50% U.T.S.	26/33	30/25	180°
From Web, A	50% U.T.S.	26/33	30/25	180°
From Web, B	50% U.T.S.	26/33	30/25	160°
From Web, C	50% U.T.S.	26/33	20	125°

Bend Specimen, $1'' \times \frac{3}{4}''$ or $1'' \times 1''$ on $\frac{1}{4}''$ radius.

35. ROTORS (BARREL TYPE).

Barrel type rotors, as used for electrical generators and other purposes, are generally forged from an entire ingot after discarding a suitable length from the top and bottom to ensure sound material.

On account of their size and importance, each rotor forging should be separately tested, even though more than one is made from the same ingot.

For such forgings it is usual to take tests from both ends of the shaft extensions and also from the end of the barrel corresponding with the top of the ingot, the latter tests being taken both in the tangential and radial directions.

Test Specimens.—Fig. 49C shows the usual arrangement of the test specimens for a large rotor forging, although in the case of the very largest forgings additional tangential and radial tests are also taken from the bottom end of the rotor barrel.

The dimensions of the tensile specimens usually employed are given by the Table I.

Test Specifications.—Physical test requirements will depend on the particular service, but average practice suggests the following, as representative of good-class carbon steel forgings.

Yield Point (min.) tons/sq. in.	U.T.S. tons/sq. in.	El. (min.) %	Angle of Bend (min.)
20	35	L. 20	180°
		T. 16	120°
		R. 16	90°

Bend Specimen $1'' \times \frac{1}{2}''$ section, on $\frac{3}{8}''$ radius.

36. ROTORS (DISC TYPE).

Forged steel rotors of the disc type are invariably tested by tangential tests cut from the rim, the tensile and bend specimens being preferably taken from diametrically opposite positions.

In certain cases, where the discs are forged with a thickened hub portion, it is also usual to take tangential tests from this position, the hub being forged specially large for the purpose.

Small discs manufactured in batches from the same ingot may be tested by selecting one representative sample for test specimens, the remainder being Brinell tested to check the uniformity of the batch.

Larger discs of the order of 2 ft. or more diameter should be tested individually.

Test Specimens.—The position of test specimens for a disc type forging made with a hub extension are shown on Fig. 49D, in which the tensile specimens are of the same dimensions as for barrel type forgings, but the bend specimens are usually made $\frac{3}{4}'' \times \frac{3}{8}''$ in section, no matter whether carbon or alloy steel be employed.

Test Specifications.—The following specification gives the usual physical requirements for carbon steel disc forgings, covering a fairly wide range in tonnage.

Yield Point (min.) tons/sq. in.	U.T.S. tons/sq. in.	El. (min.) %	Angle of Bend (min.)
50% U.T.S.	30/40	U.T.S. + El. % =55	150° on $\frac{1}{2}''$ radius former

37. PINION AND GEAR BLANKS.

These forgings vary enormously in size, from the very largest turbine reduction gears down to small forgings, one foot or less in diameter.

Testing procedure, however, for individual forgings, does not differ appreciably, except that in the larger forgings tests from the tooth blanks may be duplicated by others taken diametrically opposite.

Gear wheels forged as discs are tested by tangential specimens cut from the rim, whilst pinion forgings are provided with extensions to the shaft and barrel from which are cut longitudinal and tangential specimens respectively.

In addition, it is usual to carry out a series of hardness tests on the surface from which the teeth will be cut in order to explore the uniformity of the heat treatment.

Test Specimens.—The sketches shown by Figs. 49E and F indicate the position from which test specimens are usually taken and also mark the positions at which hardness tests are required.

Test Specifications.—Typical physical properties for non-hardened gears are given below.

	Yield Point tons/sq. in.	U.T.S. tons/sq. in.	El. (min.) %	Bend Test. Section.	Angle (min.)
Wheel,	15 min.	30/36	25	$1'' \times \frac{3}{4}''$ on $\frac{3}{8}''$ rad.	180°
Pinion,	24 min.	40/45	L.—22	$1'' \times \frac{3}{4}''$ on $\frac{3}{4}''$ rad.	180°
			T.—15	$\frac{3}{4}'' \times \frac{3}{8}''$ on $\frac{3}{4}''$ rad.	180°

38. RING FORGINGS.

The ring type of forging is a very common shape, but because of its wide range of applications, its size may vary from a few inches up to 12 or 15 feet in diameter.

Little difference occurs, however, in the procedure of testing rings, whether large or small, the test material being in practically all cases provided by an extra axial length of ring, test specimens generally being cut from positions diametrically opposed.

Test material in the case of very large ring forgings may be provided by locally increasing the width of the ring in order to avoid waste of material and machining time, such as would occur with a ring uniformly increased in width.

Small rings made in batches from the same cast may be tested by the selection of one to provide test material, the remainder being Brinell hardness tested to check the uniformity of the heat treatment.

Test Specimens.—Test specimens are cut from the spare material provided, as shown by the sketch, Fig. 49G.

In the case of large rings, it is common practice to take tensile and bend specimens from each of two diametrically opposed positions, although in the case of medium and small-sized rings it is sufficient to take a tensile specimen from the first position and a bend specimen from the diametrically opposed position.

Test Specifications.—A specification which includes for most requirements in carbon steel ring forgings is given below :—

Yield Point (min.) tons/sq. in.	U.T.S. tons/sq. in.	El. (min.) %	Bend Test. Section.	Angle (min.)
50% U.T.S.	28/40	U.T.S. + % El. = 55	$1'' \times \frac{3}{4}''$ or $1'' \times 1''$	180°

Radius of Bend : $\frac{3}{8}''$ for 28/32 tons/sq. in.
$\frac{5}{8}''$ for 32/36 ,, ,,
$\frac{7}{8}''$ for 36/40 ,, ,,

39. CARBON STEEL CASTINGS.

Steel castings may vary so widely in shape and size that, unlike the case of forgings, it is not possible to place them under classified groups for which the testing procedure can be standardised. Test material, however, should always be cast in one with the job and there is one rule common to both forgings and castings, that test material should not be separated from the forged or cast part until after the final heat treatment is completed.

The usual practice with castings is to treat each type of casting on its merits and to define the position, size and number of the test coupons according to the shape, size and importance of the cast part.

In the case of small castings, which are poured in batches all from the same ladle, it will generally be quite satisfactory to provide test material on one or two only from the batch, but if this procedure is carried out it is important that any subsequent heat treatment of the castings should be made with the whole batch placed in the furnace at the same time.

Occasionally it is more convenient and satisfactory when dealing with batches of small castings to make one or more extra castings, which are afterwards cut up to provide test material.

Larger castings which are cast individually will require individual testing and test material should be provided in the form of rectangular coupons cast on to the main casting at positions selected as being representative of the bulk

An example of the arrangement of test coupons on a large casting is shown by Fig. 49K, which illustrates the case of a large cast steel flywheel. In this example, two tests coupons are provided on the bottom boss and four on the periphery, whilst a test slab is left on the top of boss after removing the central riser.

In the particular instance quoted, tensile and bend specimens are prepared from each coupon, after separating them from the casting by sawing or other suitable means.

Physical Properties.

Carbon steel castings can for all practical purposes be divided into two groups, depending on their chemical composition, (*a*) Mild steel castings 0·13 - 0·27%C. and (*b*) High tensile steel castings 0·27 - 0·40%C.

Alloy steel castings, on the other hand, are almost invariably special jobs of a composition determined by the operating conditions and each case has therefore to be treated individually.

Reverting to the case of carbon steel castings, the approximate physical properties which can be expected from the two groups (*a*) and (*b*) are as given below :—

CARBON STEEL CASTINGS.

	U.T.S. tons/sq. in.	Y.P. tons/sq. in.	El. %	Bend ($1'' \times \frac{3}{4}''$ on $1''$ rad.)
(*a*) 0·13 - 0·27% C.	26/35	45% U.T.S.	20	120°
(*b*) 0·27 - 0·40% C.	35/40	45% U.T.S.	18	90°

40. TESTS ON ALLOY STEELS.

It has been previously pointed out that the testing of alloy steel forgings or castings cannot be dealt with in any detail, owing to the very wide range of compositions and heat-treatments met with in such materials.

There are, however, certain popular classes of alloy steels for which the physical properties in the forged conditions may be specified in order to assist in the choice of steels for special purposes.

A selection of such steels, with their approximate compositions and physical properties, is given in Table 5. It should be noted, however, that the properties quoted refer to forged steels, heat-treated, as indicated in the table.

When specifying physical properties, some allowance on the tabulated figures should be made for cast materials and for transverse tests from forgings.

Alloy steel forgings and castings are frequently small in bulk and the testing procedure would generally be to select one sample for tensile, bend and impact test, the remainder of the batch being checked for uniformity by hardness measurements.

In the special case of large alloy steel forgings or castings, the procedure of testing would be similar to that described in the cases of carbon steel forgings and castings, with the additional provision of material for impact tests.

In Conclusion.

The mechanical testing of materials and the associated testing equipment has now developed to a point where specialised training is necessary for men concerned with this aspect of engineering.

The present pamphlet within its limited size has only been able to touch very briefly on some of the more uncommon types of test and others of lesser or very specialised importance have necessarily been omitted.

TABLE No. 5. PHYSICAL PROPERTIES OF ALLOY STEELS.

Material and Treatment.	Composition %							Physical Properties.				
	C.	Mn.	Si.	Ni.	Cr.	Mo.	W.	U.T.S. tons/sq. in.	Y.P. tons/sq. in.	Elon. %	R. of A. %	Izod. ft./lbs.
3% Ni.—Steel. O.H. 840°C. T. & A.C. 650°C.	0·32	0·6	0·18	3·2	0·12	—	—	50	42	25	60	80
5% Ni.—Steel. O.H. 820°C. T. & A.C. 650°C.	0·18	0·4	0·16	5·0	0·05	—	—	45	35	25	65	70
Rustless Iron. W.Q. after Rolling at 725°%	0·07	0·15	0·3	0·15	13·5	—	—	33	25	30	70	—
Stainless Steel A.H. 950°C. T. 650°C.	0·15	0·2	0·2	0·35	13·5	—	—	45	30	25	60	70
Ni.-Cr. Steel O.H. 840°C. T. 650°C.	0·3	0·6	0·18	3·1	0·7	—	—	60	50	18	60	60
Ni.-Cr.-Mo. Steel O.H. 830°C. T. 650°C.	0·33	0·60	0·2	2·5	0·65	0·6	—	65	55	20	60	50
H.T. Stainless Steel. O.H. 950°C. W.Q. 600°C. T. 700°C.	0·3	0·25	0·2	0·5	13·2	—	—	62	45	18	45	30
Austenitic Stainless Steel. A.C. 1050°C.	0·1	0·3	0·7	8·0	18·0	Ti. 0·65	0·7	42	20	45	65	100

It is believed, however, that the scope of the pamphlet has covered a good proportion of the normal testing practice and the author trusts that the work will be helpful to those not familiar with testing appliances and procedure.

Finally, the author wishes to record his indebtedness to Sir A. P. M. Fleming, C.B.E., Director of Research and Education Departments of the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the matter of the present pamphlet and also to the many manufacturers of testing appliances and others who have so willingly supplied information and diagrams, without which the pamphlet would have lost much of its value.

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4.	Steam Radiation Heating Chart.	
5.	Horse-Power of Leather Belts, etc.	
6.	Automobile Brakes (Axle Brakes)	Connected.
7.	Automobile Brakes (Transmission Brakes)	
8.	Capacities of Bucket Elevators.	
9.	Valley Angle Chart for Hoppers and Chutes.	
10.	Shafts up to 5½-in. diameter, subjected to Twisting and Combined Bending and Twisting.	
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